Scientific Papers. Series E. Land Reclamation, Earth Observation & Surveying, Environmental Engineering. Vol. XIII, 2024
Print ISSN 2285-6064, CD-ROM ISSN 2285-6072, Online ISSN 2393-5138, ISSN-L 2285-6064

CONSISTENCY INDEX OF SOILS, CORRESPONDING TO THE STATE OF SATURATION: AN IMPORTANT PARAMETER IN ANTICIPATING THE BEHAVIOR OF COHESIVE SOILS

Ernest Daniel OLINIC[1], Tatiana OLINIC[2]

[1]Technical University of Civil Engineering Bucharest,
122-124 Lacul Tei Blvd, District 2, Bucharest, Romania
[2]University of Agronomic Sciences and Veterinary Medicine of Bucharest,
59 Marasti Blvd, District 1, Bucharest, Romania

Corresponding author email: tatiana.olinic@fifim.ro

Abstract

The physical characteristics of a soil give indication on its mechanical behavior and also offer suggestions in the correct programming of the laboratory tests, which will correctly describe the mechanical behavior of the soil. The plasticity index and the consistency index are two important parameters used to describe the cohesive soils. If the plasticity index is a nature parameter, the consistency index is a state parameter, which describes the state of the soil at its natural moisture content. The consistency index is the difference between the liquid limit and the natural moisture content, divided to the plasticity index. For the calculation of the consistency index corresponding to the state of saturation, the natural moisture content is replaced by the saturation moisture content, a situation in which, for the respective soil, the lowest state of consistency is anticipated in the assumption of its saturation. Beyond the theoretical aspects regarding the definition of this parameter, never previously used in technical literature, being an invention of the authors, the paper presents calculation examples and case studies with an emphasis on collapsible soils and swellings-shrinking soils, which represent difficult foundation conditions.

Key words: *collapsible soils, consistency index, degree of saturation, swelling-shrinking soils.*

INTRODUCTION

The physical characteristics of a soil give indication on its mechanical behavior and also offer suggestions in the correct programming of the laboratory tests, which will correctly describe their mechanical behavior of the soil. The plasticity index and the consistency index are two important parameters used to describe the cohesive soils. If the plasticity index is a nature parameter, the consistency index is a state parameter, which describes the state of the soil at its natural moisture content. Nature parameters are those who does not depend on moisture content and porosity (or void ratio). As examples, grain size distribution, skeleton density, are not influenced by those two parameters and represents nature parameters. State parameters gives real indications on soil mechanical behavior because the same soil, but with different porosity or moisture content, will behave different and even will have the behavior of a difficult soil under certain circumstances.

The highest risk in the case of foundation on difficult soils is if they are not identified by the elaborator of the geotechnical investigation as difficult foundation conditions. Is there such a risk? It can be explained, both by following the long path of carrying out a geotechnical investigation, as well as through the definition of difficult foundation conditions, defined by NP 074-2022. The geotechnical engineers commonly utilize clay index properties to estimate the geotechnical parameters (Ahmed, 2018).

The elaboration of a technical documentation regarding the geotechnical investigation of a site involves a series of stages, each of them very important: the study of relevant documents and maps, the technical visit to the site, the field investigations, the laboratory tests and the synthesis and interpretation of the results.

The study of relevant documents and maps, especially the geological, geomorphological and hydrogeological characterization of the site, can provide information on the nature and condition of the foundation soil from the site and may even indicate the presence of difficult foundation conditions. But, the existence of these soils is not always indicated on documents and maps, especially since their scale is sometimes quite small. So, there is a risk that the difficult foundation conditions are not indicated in the relevant documents and maps.

Also, visual observations from the site may not be conclusive regarding the existence of difficult foundation conditions on site.

An extremely important stage in conducting field investigations with sampling is the preparation of the primary borehole log. It must include the preliminary description of the soil, stratigraphy and groundwater table. The greater the operator's experience in the field, the closer the description of the sample will be to the final result and, above that, more useful in the stage of programming the laboratory tests.

It was demonstrated that the increase of groundwater table can cause the saturated loess exhibit a strong strain-softening behaviour, i.e., the soil strength sharply decreases until reaching its critical state around 0 kPa (Xu et al., 2022).

Laboratory tests should be scheduled through visual and tactile analysis of laboratory samples. Even in this situation, experience is decisive in correct programming of the tests.

The foundation soils are classified as good, average or difficult and represent the main factor for establishing the geotechnical category. Based on these factors, the frequency and types of field investigations and laboratory tests are established.

Fine soils are classified as foundations soils as follows:

- good if $I_c > 0.75$;
- average if $0.5 < I_c < 0.75$;
- difficult if $I_c < 0.5$.

The classification of fine soils as good, average or difficult, according to the consistency index, drew the attention of the authors of this paper to the parameter that is proposed to have a current use in geotechnical investigation reports.

It is well known that, if the water content increases, the consistency of a fine-grained soil changes from a semi-solid state to a plastic state, and eventually to a liquid state (Dolinar, 2009). The consistency index in its natural state can be higher than 0.75 or 0.5, but if the soil reaches a saturated state, this index can drop below those limits and the classification should be made according to worst case scenario.

In the list of difficult foundation soils, defined by NP 074-2022, there are also the following cohesive soils (to which the paper is addressing):

- collapsible soils (loess);
- swelling and shrinking soils.

These soils require special tests in order to classify them and subsequently, provide the necessary parameters in the geotechnical design. If these tests are not performed, the soil will be classified as medium or even good foundation soils, with major negative implications in the design and execution (Olinic, 2016).

Practically, both types of soils require special tests, including double compressibility tests in the oedometer, both on the sample at natural moisture content and on the initially saturated sample. Of course, these tests extend the execution time of a documentation regarding the geotechnical investigation, which is why it can be useful to use a parameter, which results from the simple tests of identification of physical parameters and which indicate whether it is necessary to carry out these special tests.

It is found that risks are identified in terms of the correct programming of laboratory tests, in all stages of the development of a documentation regarding the geotechnical investigation, and the difficult foundation cohesive soils covered by this paper, can sometimes be difficult to identify only after a visual and tactile analysis.

MATERIALS AND METHODS

Parameters that define swelling and shrinking soils

According to NP 126-2010, for classifying a material in the category of swelling-shrinking soils, the following geotechnical parameters must be determined and calculated, based on laboratory tests:

$A_{2\mu}$ - percentage of clay (d < 0.002 mm);
I_P - plasticity index;
I_A - activity index ($I_A=I_P/A_{2\mu}$);
C_P - plasticity criterion [$C_P=0.73(w_L-20\%)$];
U_L - free swell;
p_u - swelling pressure.

Depending on these parameters, soils are characterized by low, medium, high and very high activity in relation to water. Unfortunately, the standard does not indicate whether all or only a part of these parameters must include the soil in those categories. Practically, the regulation requires that, in order to be sure that a cohesive soil is correctly identified as swelling-shrinking soil or not, all these tests must be performed. But, it is found that the first 5 parameters are the parameters of nature. Basically, they indicate the fact that, if the respective soil has certain moisture content and certain porosity, it will be swelling-shrinking soil, without any certainty in this regard. In current practice, especially the activity index provides erroneous information (Olinic et al., 2014).

The swelling pressure is certainly the most important parameter of a swelling-shrinking soil, but NP 126-2010 and STAS 1913/12-88 describe different procedures, for its determination, with positive and negative implications in the results. Worldwide there are several methods for the determination of the swelling pressure.

In some geotechnical problems, the behavior of clay after failure is as much important as the behavior of clay before failure (Atkinson, 1978).

Parameters that define collapsible soils

According to NP 125-2010, to characterize a soil as collapsible (loess), there are 2 criteria related to physical properties and 2 related to mechanical behavior, of which at least one must be met.

In current practice, the physical criteria refers to:

- silt fraction (d = 0.002 - 0.062 mm) to represent de 50- 80% of total dry mass;
- unsaturated state ($S_r < 0.8$);
- porosity, n > 40%.

By laboratory tests, the criterion related to the mechanical behavior is that the additional specific settlement index by wetting under the stress of 300 kPa (in the oedometric test), i_{m300}, has a value greater than or equal to 2%. The second mechanical criterion involves tests with the plate load test on the soil at natural moisture content and on saturated soil, a method not currently used in common practice.

Loess is a silty soil in which the constitutive chemical connections are susceptible to degradation by water, resulting in irreversible moisture-related damage (Leng et al., 2021).

It should be relatively easy to identify a loess by visual inspection, especially due to the macropores, the small mass and the yellowish-brown color. But, there is also within this material a particular risky situation in which it does not stand out as sensitive to water soil: when the soil has $S_r > 0.8$ and the geological stress is lower than the structural resistance, a situation in which, both in the field and in laboratory tests, it will not register additional settlement to wetting but, in the hypothesis of lowering the underground water level, it will become again a collapsible soil.

Structural resistance of a collapsible soil is the minimum pressure for which the behavior (settlement) of the saturated soil is different (higher) than the one at natural moisture content. This value varies between 20 and 250 kPa (cannot be higher than 300 kPa due to the definition of the loess).

RESULTS AND DISCUSSIONS

The definition of consistency index of soils, corresponding to the state of saturation

The consistency index is the difference between the liquid limit and the natural moisture content, divided to the plasticity index (Casagrande, 1948).

$$I_C = \frac{w_L - w}{I_P} \quad (1)$$

For the calculation of the consistency index corresponding to the state of saturation, the natural moisture content is replaced by the saturation moisture content, a situation in which, for the respective soil, the lowest state of consistency is anticipated in the assumption of its saturation.

$$I_C{}^{sat} = \frac{w_L - w_{sat}}{I_P} \quad (2)$$

For the calculation of the consistency index corresponding to the state of saturation, it is necessary to determine in the geotechnical laboratory, through specific tests: the moisture content (w), the plastic limit (w_P), the liquid limit (w_L), the density in the natural state (ρ) and the density of the mineral skeleton (ρ_s), simple, usual tests and which are not very long time consuming.

From the calculation point of view:

$$I_C{}^{sat} = f(w_P, w_L, n, \rho_s) \quad (3)$$

Scientific Papers. Series E. Land Reclamation, Earth Observation & Surveying, Environmental Engineering. Vol. XIII, 2024
Print ISSN 2285-6064, CD-ROM ISSN 2285-6072, Online ISSN 2393-5138, ISSN-L 2285-6064

From a database that includes 4000 soils from Romania (Figure 1), it appears that w_P varies between 10 and 30%, while w_L varies between 20 and 100%, values also confirmed by technical literature.

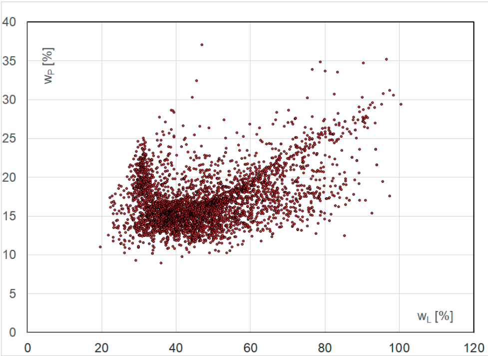

Figure 1. The variation of w_P and w_L obtained for 4000 soil samples from Romania

Figure 2 shows variation graphs of I_c^{sat} depending on soil porosity, for the minimum, intermediate and maximum values of w_P and w_L from the database.

In Figure 2.a and Figure 2.c the variation of I_c^{sat} is represented considering w_P = 10% and ρ_s = 2.67 g/cm^3, respectively, ρ_s = 2.72 g/cm^3. There are typical values for soils with low and average plasticity. For this reason, the lines of w_L = 70 and 100% are represented dotted.

It is found that the minimum (theoretical) value of I_c^{sat} is almost -0.4, which corresponds to the liquid state of the soil, a state in which it is impossible to meet a soil in its natural state. But a soil with I_c of a certain value can be encountered and, if for I_c^{sat} values are obtained from very low to liquid consistency, this should be an alarm signal for a more detailed analysis of the respective soil.

With reference to a collapsible soil (loess), it has the porosity between 40 and 55% and, for a plastic limit of 35%, the I_c^{sat} varies between -0.4 and 0.4.

In Figure 2.b and Figure 2.d, the variation of I_c^{sat} is represented considering w_P = 30% and ρ_s = 2.67 g/cm^3, respectively, ρ_s = 2.72 g/cm^3. There are typical values for soils with high and very high plasticity. For this reason, the w_L = 35% line is represented dotted.

In this case, it is found that a soil, even with a porosity of 55%, in the assumption of its saturation, will at most reach a soft consistency state.

For porosity in the usual range of cohesive soils, of 35-45%, it is found that, even in a saturated state, the soil has a state of solid consistency. This situation should raise an alarm signal, in the sense that the soil in question is, most likely, in the category of swelling and shrinking soils.

Figure 3 shows the variation of I_c^{sat} depending on the porosity, for a usual value of the liquid limit, w_P = 20% and ρ_s = 2.7 g/cm^3. These are average values, often found in current practice. In this graph, the area where swelling-shrinking soils is indicated, respectively, the collapsible soils or soils with very high compressibility.

The graph can be used as an abacus for the quick determination of I_c^{sat} depending on the porosity and the plastic limit of the soil.

The Consistency index of soils, corresponding to the state of saturation, determined on collapsible soils

A database with physical and mechanical determinations made on soil samples collapsible soils (loess) was accessed and I_c^{sat} was determined.

Figure 4 shows the results of several tests performed on loess, respectively, the variation of I_c - I_c^{sat} and i_{m300} depending on the porosity. It is noted that, for the selected samples, the Ic in the natural state of the loess is between 0.8 and 1.8, for which the soil is classified as stiff and solid consistency.

In saturated state, the loess reaches a consistency index between -0.44 and 0.58, for which the soil has a consistency from liquid to very-soft, soft and medium-soft.

In the same plot, the additional specific settlement to wetting of the existing soils in the database is also represented.

The results confirm the previously mentioned theoretical aspects.

CONCLUSIONS

In this paper, it is proposed to be implemented the consistency index corresponding to the state of saturation (I_c^{sat}) as a physical state parameter, useful in engineering judgment, in terms of identifying cohesive soils classified as difficult foundations soils, respectively, collapsible soils, swelling-shrinking soils or soils with very high compressibility which, in their natural state, can register a high consistency index (stiff to solid consistency) but, in the assumption of saturation, it becomes with soft, very-soft or even liquid consistency, with major implications in reduction of the mechanical behavior.

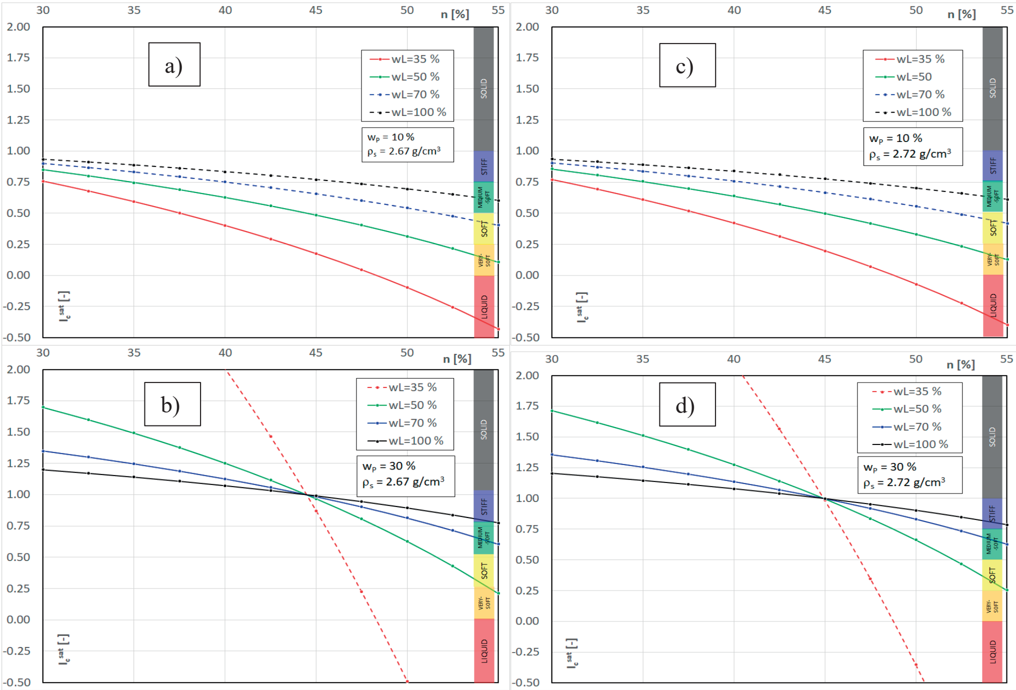

Figure 2. The variation of I_c^{sat} depending on the porosity and plasticity - extreme values

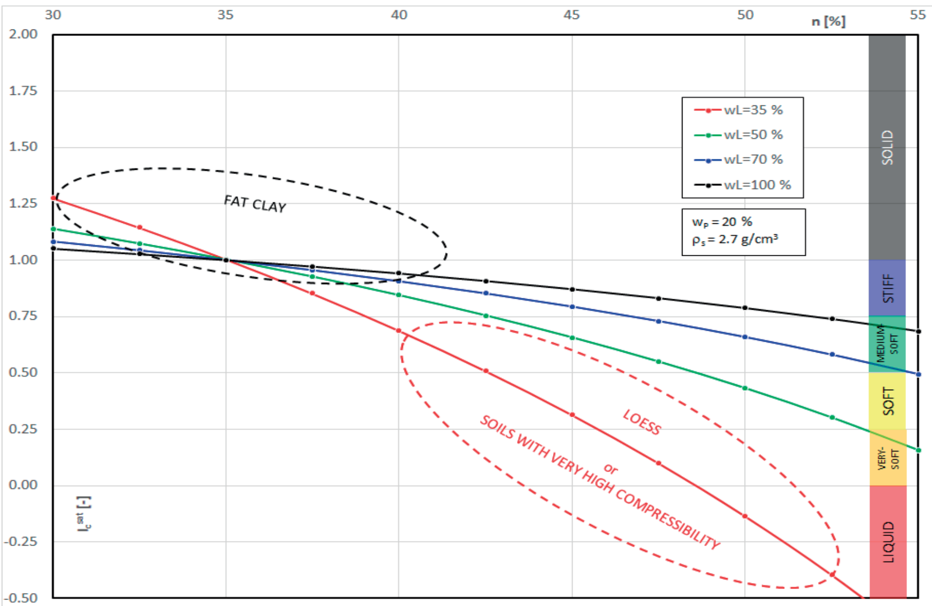

Figure 3. The variation of I_c^{sat} depending on the porosity and plasticity - usual values

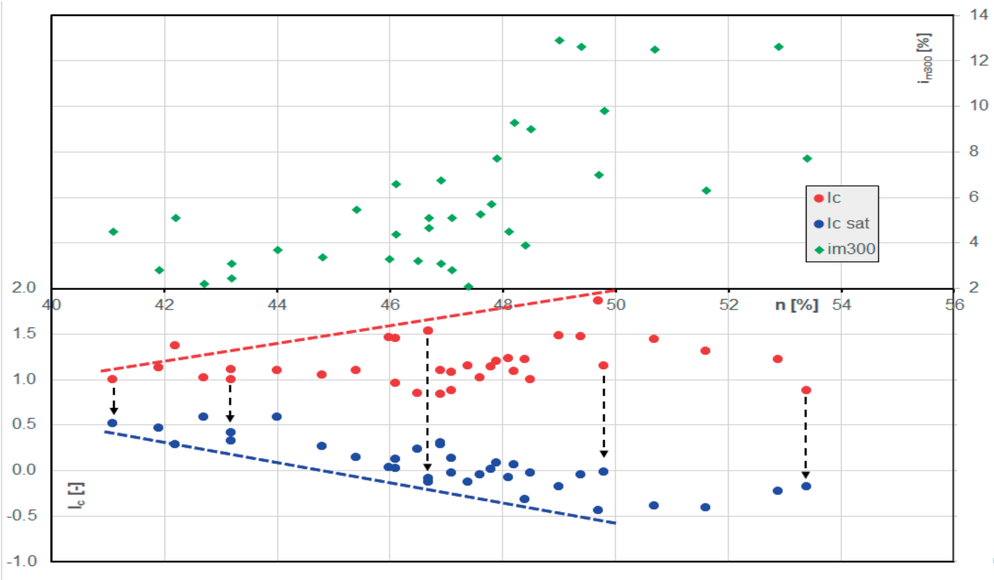

Figure 4. I_c^{sat} for several samples of loess (collapsible soils)

The consistency index corresponding to the state of saturation can be useful, both in the correct programming of laboratory tests, as well as in the expert analysis of some geotechnical documentation in which no difficult foundations were correctly identified.

The classification of cohesive soils as good, medium, or difficult, depending on the consistency index at natural moisture content, as requested in NP 074-2022, should be done according to the consistency index corresponding to the saturation state of the soil (I_c^{sat}).

REFERENCES

Atkinson, J.H., Bransby, P.L. (1978). *The Mechanics of Soils, an Introduction to Critical State Soil Mechanics.* McGraw-Hill Book Company, England, UK, 375 pp.

Ahmed, S.M. (2018). Assessment of clay stiffness and strength parameters using index properties. *Journal of Rock Mechanics and Geotechnical Engineering*, *10*(3), 579-593.

Casagrande, A. (1948). Classification and identification of soils. *Transactions of the American Society of Civil Engineers*, *113*(1), 901-930.

Dolinar, B. (2010). Predicting the normalized, undrained shear strength of saturated fine-grained soils using plasticity-value correlations. *Applied clay science*, *47*(3-4), 428-432.

Leng, Y., Peng, J., Wang, S., Lu, F. (2021). Development of water sensitivity index of loess from its mechanical properties. *Engineering Geology*, *280*, 105918.

Olinic, E., Ivasuc, T., Manea, S. (2014). Mechanical behavior of destructurated expansive clay. *14th International Multidisciplinary Scientific Geoconference*, Science and Technologies in Geology, Exploration and Mining - Conference Proceedings, Vol. II., 581 -589, Albena, ISBN 978-619-7105-08-7.

Olinic, E. (2016). Difficult foundation conditions in Romania. *Proc. 25th European Young Geotechnical Engineers Conference*, 37-53, 21-24 June 2016 - Sibiu, Romania, Publishing House Conspress, ISBN 978-973-100-421-1.

Xu, L., Gao, C., Zuo, L., Liu, K., Li, L. (2022). The critical states of saturated loess soils. *Engineering Geology*, *Vol. 307*, 106776, ISSN 0013-7952, (https://doi.org/10.1016/j.enggeo.2022.106776).

***NP 074-2022. Technical norm regarding the geotechnical documentations for constructions.

***NP 125-2010. Technical norm regarding the foundation of constructions on soils sensitive to wetting.

***NP 122-2010. Technical norm regarding the determination of the characteristic and calculation values of the geotechnical parameters.

***STAS 1913/12-88 Foundation soil. The determination of the physical and mechanical characteristics of the swelling and shrinking soils.