Analysis of behavior of soil compressibility of the lacustrine deposit of Tunja, Colombia

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Abstract. This article contains the research results in the evaluation of a mathematical model for the determination of the compressibility coefficient of the soils of the lacustrine deposit of the city of Tunja, Colombia, through the execution of one-dimensional consolidation tests, complementary with soil classification tests characterizing its index properties, stories as a ratio of voids, porosity, specific gravity and consistency limits, where a selection of different sites located covering the general area of the lake deposit is made, taking soil samples unaltered at different depths, where processed these soil samples for later geotechnical evaluation. A series of mathematical expressions were generated to determine the approximate shape of the compression coefficient, depending on the index properties, discretizing according to the type of soil, where for this case clays of low and high plasticity were found as silt of high plasticity. These models will serve as a tool to determine the approximate and preliminary form of the magnitude of the main compressibility coefficients.

1. Introduction

All engineering work regardless of its dependence, whether road, hydraulic or structural, is built directly or indirectly on the ground, so in any type of construction the analysis and understanding of the behavior of the material responsible for the geotechnical stability of the building is fundamental, since depending on the characteristics of the soil the type of foundation to be used is selected. The importance in the selection of this part of the structure has no limits, since the appropriate choice of foundation will depend on the magnitude of the settlements that will appear in the future, which are deformations that are produced by the increase of effective efforts [1].

Within the capabilities of the civil engineer is the prediction of these settlements by studying the consolidation phenomenon, which is why over time have been exposed several theories that allow modeling this phenomenon by conducting laboratory tests that evaluate the relationship between efforts, deformations and time; these deformations are the result of a decrease in the ratio of voids, which reduces the total volume of the soil mass, considering that the volume of solids is constant, the deformation present in the soil is generated by the release of water into permeable strata , allowing the rearrangement of the solid particles in the now empty spaces. At the beginning of the 20th century, the phenomenon of consolidation was known [2], beginning a series of theories, among them, the theory of one-dimensional consolidation, which is still used in the realization of this kind of tests, there were many authors who investigated this phenomenon and issued correlations according to their results to determine the consolidation coefficient of the soil based on parameters easier to estimate such as
specific gravity (Gs) and index properties, in many cases raising its applicability to specific types of clays or common soils of its surroundings, which limited its application.

The purpose of this research work is to evaluate a series of correlations based on consolidation parameters that are usually used in land classification issues, this applied to the characteristic soils of the deposit present in the city of Tunja, Colombia, which will allow be used as a tool for the preliminary characterization of this type of soils, which are characteristic of tropical sedimentary environments, allowing to know locally their behavior and this in turn compared to theories present in the literature and that it is known that sometimes these They do not fit correctly to the behavior of this type of soil.

2. Compressibility analysis

In the study of the effect of compressibility of a soil mass depends on the stiffness of the skeleton. The rigidity in turn depends on the mineralogical composition and the structural arrangement of the particles in and these that are so linked together [3].

The most important characteristics of compressibility of soils exhibited in the consolidation stage are the compressibility index (Cc), which relates how much compressibility by consolidation will take place in the soil, the consolidation coefficient (Cv) that indicates the speed of consolidation [4] and the degree of settlement of the soil under a certain load increase linked to the speed of this [5], and the recompression index (Cr), which represents the ease with which the soil recovers its original form a Once it is downloaded, where it is recorded that this value is between 1/4 to 1/10 of the Cc [6]. Their values are determined by laboratory tests using odometers.

The value of Cc varies according to the type of soil and its properties, which is why several authors have come to propose correlations for their determination based on easily applied index properties, such as in Equation (1), it was presented correlation of Cc as a function of the liquid limit (LL) for clays normally consolidated proposed by [7], Equation (2), as a function of the LL and Gs limit proposed by [8], Equation (3), as a function of porosity (n) [9], Equation (4), as a function of Gs and plastic index (IP) and finally in Equation (5) as a function of IP [10]. It is possible to classify soils as low compressibility where Cc<0.2, medium compressibility where 0.2<Cc<0.4 and high compressibility for Cc>0.4, according to the value of this coefficient [11].

\[
C_c = 0.009(LL - 10) \tag{1}
\]

\[
C_c = 0.2343 \times \left[\frac{LL}{100}\right] \times Gs \tag{2}
\]

\[
C_c = \frac{n}{371.747 - 4.275 n} \tag{3}
\]

\[
C_c = 0.5 \times Gs \times \left[\frac{IP}{100}\right] \tag{4}
\]

\[
C_c = \frac{IP}{74} \tag{5}
\]

At the national level, in 2004 a study was carried out on the clay soils of the lacustrine deposit of Tunja, in which the directly specific correlations of the soils with specific characteristics of the study area were determined, the affected results are presented in the Equation (6) presented as a function of LL [12], Equation (7) expressed as a function of plastic limit (LP) and Equation (8) expressed as a function of contraction limit (LC).

\[
C_c = (0.042 \times LL) - 0.0827 \tag{6}
\]

\[
C_c = 0.3298 \times \ln(LP) - 0.8889 \tag{7}
\]
In this same year, in Mexico City, a research work is elaborated in the International Polytechnic Institute called "Study of the compressibility properties of the clays of Coatzaolcoa", in which the author affirms that the equations proposed by authors such as Terzagui and Peck, Lambe and Whitman, Kulhawy and Mayne to determine $C_c$ values are thought to be applied universally to normally consolidated inorganic clays, and others for soils of certain regional areas, which means that the aforementioned equations have no logical basis to justify its development. The above shows the inapplicability and low precision of the compression index values determined from these expressions. On the other hand, the secondary consolidation is the product of the rearrangement of mineral particles consisting of small relative slides, turns and turns of some particles with respect to others, which are adapting to a more closed structure and smaller volume, which becomes more evident in the last stages of the primary consolidation process [13], mainly in highly compressible soils, that is, it is defined as the volumetric reduction that occurs when the pore pressures have dissipated and the load in its entirety is supported by the skeleton of the soil [14].

### 3. Study site

The specific area of study corresponds to the lake deposit, which predominates in the city of Tunja and covers a large part of the north-eastern sector of the same. It is formed by silts with intercalations of sand and clay of brown color and variable plasticity, with reddish oxidations. It includes the valleys of humidity the River Chulo and the River Cascada, with a morphology of soft to flat relief. The thickness of the deposit reaches 50 m on the axis of the syncline and lie discordantly on the Tilatal formation formed by a set of sandy clay [15]. Its approximate delimitation allows us to infer that it contemplates the North arbor, the districts Mesopotamia, Santa Inés, Las Quintas, Los Muiscas, Unicentro, among others. It is noteworthy that in the eastern and western extremes the deposit presents transitional sectors where the materials vary from fine to granular according to the strata [16].

### 4. Experimental results

For the compressibility analysis of the lacustrine deposit in the city of Tunja, Colombia, 21 samples from 12 surveys conducted in different sectors of the deposit were evaluated and taken at different depths. Figure 1 shows the distribution of the surveys carried out, from which the specimens of interest for this study were extracted. Together, all specimens taken as a representative sample characterize a large part of the deposit, reaching depths from 1.6 m to 30 m. Table 1, shows the results of the tests carried out for each of the corresponding samples, obtaining the following values: $G_s$: $2.329 - 2.797$, $LL$: $22\% - 64\%$, $LP$: $11\% - 33\%$, $LC$: $6.2\% - 19.9\%$, $IP$: $8\% - 38\%$, natural moisture ($W_n$): $6.71\% - 56.48\%$, $n$: $12.1\% - 57.2\%$, void ratio ($e$): $0.217 - 1.552$, $Cc$: $0.001 - 0.200$, $Cr$: $0.001 - 0.070$, and finally in the last column the classification according to the unified soil classification system (USCS).

$$C_c = 0.2776 \times \ln (LC) - 0.5265$$

(8)
Table 1. Summary of results.

| Sample | GS (%) | LL (%) | LP (%) | LC (%) | IP (%) | Wn (%) | n (%) | e | Cc | Cr | Type of soil |
|--------|--------|--------|--------|--------|--------|--------|------|---|----|----|--------------|
| S1-M1  | 2.557  | 64     | 33     | 7.4    | 31     | 39.81  | 17.8 | 0.831 | 0.027 | 0.005 | MH           |
| S1-M2  | 2.433  | 59     | 25     | 19.3   | 34     | 6.710  | 22.8 | 0.297 | 0.054 | 0.019 | CH           |
| S2-M1  | 2.463  | 39     | 12     | 1.4    | 27     | 21.27  | 12.1 | 0.448 | 0.007 | 0.001 | SC-SM       |
| S3-M1  | 2.524  | 49     | 16     | 13.6   | 33     | 21.49  | 16.9 | 0.217 | 0.153 | 0.057 | CL           |
| S2-M2  | 2.615  | 63     | 25     | 8.0    | 38     | 23.96  | 30.6 | 0.472 | 0.131 | 0.030 | CH           |
| S4-M1  | 2.605  | 30     | 12     | 10.5   | 18     | 21.11  | 31.5 | 0.446 | 0.090 | 0.009 | SC           |
| S5-M1  | 2.606  | 30     | 13     | 6.9    | 17     | 14.24  | 27.2 | 0.381 | 0.089 | 0.014 | CL           |
| S2-M3  | 2.548  | 30     | 15     | 12.1   | 15     | 14.84  | 33.2 | 0.524 | 0.127 | 0.015 | CL           |
| S3-M2  | 2.487  | 54     | 21     | 9.0    | 33     | 56.48  | 52.0 | 1.107 | 0.159 | 0.029 | CH           |
| S2-M4  | 2.517  | 58     | 30     | 7.2    | 28     | 112.8  | 55.8 | 1.552 | 0.321 | 0.070 | MH           |
| S6-M1  | 2.635  | 46     | 23     | 15.3   | 23     | 11.52  | 23.8 | 0.313 | 0.005 | 0.001 | CL           |
| S7-M1  | 2.344  | 64     | 28     | 19.9   | 36     | 17.98  | 31.1 | 0.472 | 0.131 | 0.046 | CH           |
| S8-M1  | 2.468  | 57     | 25     | 15.9   | 32     | 25.87  | 34.2 | 0.520 | 0.014 | 0.003 | CH           |
| S9-M1  | 2.426  | 32     | 20     | 14.7   | 12     | 32.82  | 39.5 | 0.673 | 0.200 | 0.038 | CL           |
| S4-M2  | 2.425  | 51     | 22     | 10.3   | 29     | 22.65  | 32.3 | 0.494 | 0.101 | 0.028 | CH           |
| S4-M3  | 2.422  | 22     | 11     | 9.1    | 11     | 10.53  | 19.6 | 0.249 | 0.090 | 0.022 | SC           |
| S10-M1 | 2.329  | 45     | 18     | 6.2    | 27     | 28.38  | 32.6 | 0.485 | 0.178 | 0.029 | CL           |
| S11-M1 | 2.440  | 33     | 14     | 13.4   | 11     | 51.35  | 45.5 | 0.869 | 0.053 | 0.012 | CL           |
| S3-M3  | 2.491  | 27     | 14     | 12.4   | 13     | 12.10  | 41.8 | 0.719 | 0.099 | 0.001 | SC           |
| S12-M1 | 2.577  | 28     | 20     | 16.1   | 8      | 11.41  | 22.7 | 0.309 | 0.132 | 0.023 | CL           |
| S12-M2 | 2.797  | 64     | 33     | 8.1    | 31     | 53.72  | 57.2 | 1.448 | 0.149 | 0.049 | MH           |

The tested soils are classified according to the plasticity charter of Casagrande as shown in Figure 2, finding that 57% correspond to medium or low plasticity inorganic clays (CL), 29% correspond to high plasticity inorganic clays (CH) and the rest correspond to inorganic silts of high plasticity, or with sand content (MH).

The hydrometer test was carried out with the purpose of identifying the percentage of each fine material present in the samples and the presence of sandy materials with plastic characteristics, identifying three samples corresponding to clay-sand materials and a clay-silty-sand.

Figure 2. Representation of the IP Vs LL according to the plasticity letter of Casagrande.
According to the information presented in Table 1, and in order to establish expressions that allow preliminary determination of the values of the compression coefficient based on the index properties such as Gs, LL, LP, LC, IP, n, e, an analysis was carried out that related these parameters to the series of data without discriminating according to the type of soil, evaluating their level of correlation to verify their reliability.

Of the obtained equations, the one that presented the highest correlation coefficient was the ratio of voids, with a value of $R^2 = 0.2214$, when this relationship is significant, the soil will show greater deformation when faced with an incident load, so it turns out to have higher values in soils clayey than sandy. It is noteworthy that although this is the best correlation obtained, it turns out to be low. It is because of the above that the method of grouping the data is considered not adequate, since it generates low reliability models.

A grouping of the data is carried out according to the type of soil (low plasticity clay, high plasticity clay and high plasticity silt), bearing in mind that it is not possible to generate an expression of high reliability taking into account all the data. Likewise, based on what is described in the individual analysis of the samples, some trials yield unreliable results according to the type of soil, with very low Cc values, which cause a lower correlation factor in the applied regressions, so that five of the Cc and Cr values will not be considered in the following analysis. Soils classified as clayey sands and clay-silty sands were removed from the data series, because in these soils the compressibility properties are not appreciable. The same index properties of the previous analysis are plotted as a function of the compression coefficient.

The Cc in function of the Gs shows great dispersion among the data, showing very low correlation coefficients. This indicates the high variability that this parameter has in the soils evaluated. In the same way, it happens with the LC, which does not manage to represent any relation with the Cc, with the exception of the limits greater than 10 for clays of low plasticity, where when increasing the LC, the value of Cc also increases, while for high plasticity clays, the correlation coefficient of the two variables studied is 0.53. Contrary to this, when evaluating the behavior of the LL, LP, IP, n and e, a grouping of the data is observed, where in all the graphs there are agglomerations according to the type of material. Reviewing all the variables, it will be observed that by grouping clayey soils of low and high plasticity, such as silt of high plasticity, a better result is obtained, relating the Cc with LC, LP, IP and LL, so that the following are shown respective results.

The models obtained for clay of high plasticity, low plasticity, and high plasticity silt, are presented in Equation (9) to Equation (11) and Figure 3 to Figure 5.

$$C_c = 1.4024 \cdot LC^{-1.093}$$  \hspace{1cm} (9)

![Figure 3. Mathematical model based on LC for high plasticity clays.](image)

For clays with low plasticity, Equation (10) is considered, see Figure 4.
\[ C_c = 0.0144 \times LP - 0.0928 \]  

(10)

Figure 4. Mathematical model based on the LP for clay of low plasticity.

\[ C_c = -0.448 \times \ln \left[ \frac{IP}{LL} \right] + 1.3523 \]  

(11)

Figure 5. Mathematical model based on the IP and LL for silt of high plasticity.

5. Conclusions

Of the tested soils, it was found that the clays of low plasticity correspond to 38.1%, the clays of high plasticity to 28.6%, the silts of high plasticity to 14.3% and the argillaceous sands to 19%. This last material was not considered in the generation of mathematical models because consolidation is not noticeable in this type of materials.

The \( C_c \) increases to the extent that the percentage of clays does, and decreases as the percentage of sands increases, given that the plasticity is representative of laminar structures due to its ability to undergo deformations without breaking overloads, whereas in granular structures the efforts are distributed and due to the characteristics of their particles, they are less compressible.

The high plasticity clays generated different reliable models, with high correlation coefficients. However, the best response model corresponds to the contraction limit, while for low plasticity clays they have a better performance in relation to the plastic limit, in the same way for high plasticity silt corresponds to the ratios of the plastic index and liquid limit in its evaluation, so for this type of soil analyzed, a good behavior in its application is evidenced by the equations presented here.
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