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Compressibility Behavior of Residual Soils in the Colombian Andes Under Constant Rate of Strain

Diego I. GALEANO-PARRA[a,1], David G. ZAPATA-MEDINA[a], Luis G. ARBOLEDA-MONSALVE[b] and Gaspar MONSALVE[a]
[a] *Universidad Nacional de Colombia, Sede Medellín, Medellín, 050034, Colombia*
[b] *University of Central Florida, Orlando, FL 32816, USA*

Abstract. Residual soils are developed at inter-tropical latitudes where climate conditions favor the in-situ weathering of the intact rock. They are characterized by a porous structure with high void ratios that makes them susceptible to large deformations. Soil compressibility in residual deposits is usually evaluated based on conventional Incremental Loading (IL) consolidation tests which can take up to a week to be completed and yield very limited stress-strain data. This paper employs the results of Constant Rate of Strain (CRS) consolidation tests to evaluate the compressibility behavior of two residual soils derived from igneous-metamorphic basement located around the city of Medellin, Colombia. CRS testing significantly reduces testing time and provides continuous pore water pressure and load-deformation data leading to a better definition of the yielding stress of the material. Testing was performed on hand-trimmed specimens cut from high-quality block samples. For each site, one IL and three CRS tests at different strain rates were completed. It was found that CRS testing accelerates the definition of compressibility parameters with respect to conventional IL tests and yields very similar results to conventional oedometer tests. CRS testing can be used to study strain rate dependency in the definition of the yield stress of the tested residual soils. These values increased 22% for strain rates of 20%/hr with respect to average values estimated from IL testing.

Keywords. Compressibility, residual soils, soil behavior, constant rate of strain, yielding stress.

1. Introduction

The estimation of settlements and distortions during the shallow foundation design phase in cohesive soils is a fundamental issue in geotechnical engineering. The one-dimensional (1D) small strain consolidation theory proposed by Terzaghi [1] for saturated soils has been widely used and was later generalized for three dimensional consolidations coupling the soil deformation and pore pressure [2]. This theory was extended to large strain [3], and to unsaturated soils [4-5]. Since then, different methods and procedures to estimate settlement in cohesive and granular soils have been a topic of interest of many researchers [6-8, among others]. Generally, these theories are based on

[1] Corresponding author. Dept. de Ingeniería Civil, Calle 65 No. 78-28, Bloque M1-201, Medellín, Colombia. E-mail: digalean@unal.edu.co

experimental data, therefore, estimation of representative compressibility parameters is essential during the design phase.

Residuals soils are preferentially developed at inter-tropical latitudes. At these locations, climate conditions favor the in-situ mechanical and chemical weathering that modify the structure and primary minerals of intact rock. Weathering effects in the physical characteristics and mechanical properties of the residual soils are related to the increase in porosity [9], decrease in stiffness and soil density [10], and decreasing in apparent density [11]. In addition, washing and leaching of the soil during infiltration induce mineral loss originating a residual soil with a porous structure and high void radios, which makes them highly compressible with a tendency to exhibit rapid consolidation [10]. Another important characteristic of residual soils is that these soil deposits do not undergo a consolidation process [9], and consequently, their properties cannot be related to stress history. However, for these type of soils, accurate estimation of the yielding stress, σ_y', is essential.

Current geotechnical practice uses conventional Incremental Loading (IL) consolidation tests to evaluate compressibility in residual soils. Alternatively, Constant Rate of Strain (CRS) consolidation tests can be used to study soil compressibility. In this test, excess pore water pressures are measured, and continuous load-deformation data is obtained, leading to a better definition of yield stress (σ_y'). This paper presents a critical review of the results obtained from IL and CRS tests conducted on residual soil specimens trimmed from high-quality block samples extracted from two different sites around the city of Medellin, Colombia. Given that the soil is not prone to collapse, CRS testing accelerates the definition of compressibility parameters with respect to conventional IL tests and yields very similar results to conventional oedometer tests.

2. Experimental Program and Setup

2.1. Site Description and sampling

High-quality block samples were obtained from two sites located around the city of Medellin, Colombia, at the northern end of the Central Cordillera in the Colombian Andes. The soils correspond to residual soils formed by weathering of igneous-metamorphic basement. From examination of the recovered samples and direct inspection inside deep test pits, the soil profiles belong to the lithological VI [12]. Geological unit exhibits an advanced process of weathering favored by the humid tropical climatic and topographic conditions. The experimental program and index properties are summarized in Table 1. Samples recovered at 5 m and 4 m from sites 1 and 2, respectively, were used for this study. Based on the Unified Soil Classification System [13], the tested soils were classified as high plasticity silts (MH). Plastic limits were about 45% and 43% for sites 1 and 2, respectively. Natural water content averaged 48% for site 1 and 44% for site 2. The average in-situ void ratios, e, are 1.37 for site 1 and 0.96 for site 2, with corresponding standard deviations of 0.05 and 0.08, respectively.

2.2. Laboratory Equipment and Testing Procedures

CRS test were conducted on a Constant Rate of Strain device manufactured by GDS Instruments Ltd. Specimens were 50 mm in diameter and 22 mm in height. Figure 1 shows a schematic view of the oedometer cell, loading frame and pressure/volume controller. Axial displacement, axial load, and pore water pressure were measured using an external LVDT, an internal submersible load cell, and a pore pressure transducer connected at the base of the specimen, respectively. Cell/Backpressure was applied via an advanced digital pressure controller with a range of 1,000 kPa and a volumetric capacity of 200 cm^3. The specimens were placed between two porous plates and constrained in a fixed stainless-steel ring to reduce friction and assure K_0-conditions. Drainage was allowed at the top of the sample while pore water pressures were measured at the base.

Table 1. Sample identification and index properties.

Specimen ID	Test Type and Conditions	Site	σ'_{vo} (kPa)	Void ratio	w (%)	w_{LL} (%)	w_{PL} (%)
IL-1	Incremental Loading	1	110	1.363	48	78	45
IL-2	Incremental Loading	2	80	1.271	45	69	43
S1-CRS-1	Loading axial strain rate = 1%/hr	1	110	0.802	48	78	45
S1-CRS-10	Loading axial strain rate = 10%/hr	1	110	1.267	49	78	45
S1-CRS-20	Loading axial strain rate = 20%/hr	1	110	1.181	48	78	45
S2-CRS-1	Loading axial strain rate = 1%/hr	2	80	0.931	44	69	43
S2-CRS-10	Loading axial strain rate = 10%/hr	2	80	0.892	45	69	43
S2-CRS-20	Loading axial strain rate = 20%/hr	2	80	0.989	44	69	43

Note: IL: Incremental Loading, CRS: Constant Rate of Strain.

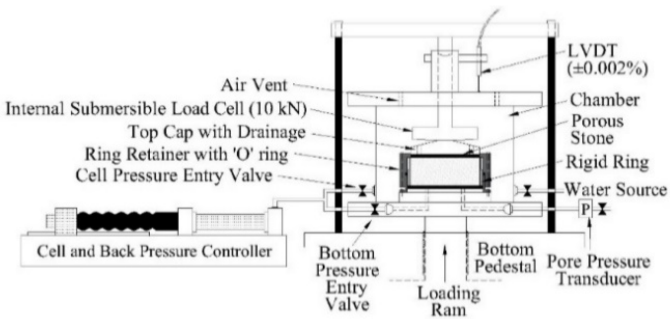

Figure 1. Schematic diagram of constant rate of strain (CRS) device.

Once the cell was assembled and filled with de-aired water, the LVDT reading was monitored to track volume changes during the entire testing sequence. Figure 2 shows typical LVDT readings and vertical effective stresses, σ'_v, versus time for all stages during CRS testing. CRS tests were completed in ten stages. Note that during the creep stages, under saturated conditions and different stress levels, abrupt volume changes were not observed (i.e. stages 5, 7 and 9), indicating that the tested soils are not susceptible to collapse or expansion. An initial vertical load (i.e., setting load) of 0.005 kN was applied to make the porous stone and load cell contact with the specimen.

Saturation of the sample was achieved by applying a back pressure of 250 kPa in an increasing ramp over 4.5 hrs. Sufficient saturation was checked by applying an increment in the chamber pressure of 25 kPa as the base excess pore water pressure, u_b, was monitored. After saturation, the line at the bottom of the specimen was closed, and the samples were loaded under strain-controlled conditions at constant rates of 1, 10 and 20 %/hr. Two cycles of loading and unloading as well as creep stages before reversing the load under constant effective stresses were performed. The specimens were unloaded at the same strain rate used in the loading phase.

IL tests were performed on a fixed ring oedometer cell with double drainage and equipped with digital readings of axial deformation. The samples were hand-trimmed to 50.8 mm in diameter and 19.075 mm in initial height. IL tests were completed using load-increment ratios of 1.0. To minimize the effect of secondary compression, IL test were conducted following method B of ASTM D2435 [13] (i.e., once 90% of consolidation is achieved, subsequent load increments are applied). The load was applied through calibrated weights on a lever system. For all specimens, an unload-reload cycle was included once the vertical effective stress exceeded the σ'_y.

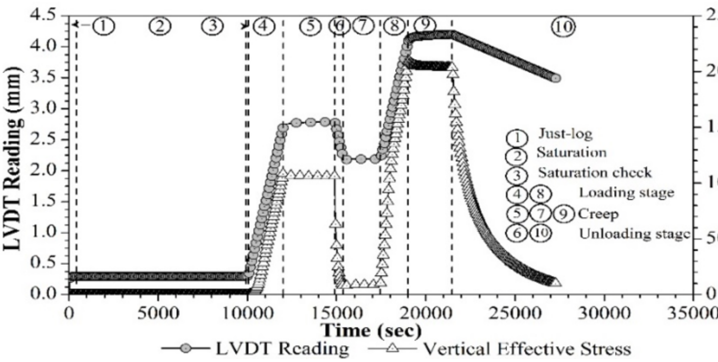

Figure 2. Typical axial displacement and vertical effective stress response during CRS Testing.

3. Results of Experimental Program

Proper deformation rate selection to avoid strain rate effects on the compressibility characteristics of the material is the most important parameter to conduct CRS consolidation tests. Several methods and theories have been developed to determine the strain rate for different types of soil [14-18]. In this study, the strain rates were selected to assess the applicability of the recommendations provided by ASTM D4186 [13]. It suggests strain rates that produce a pore pressure ratio, R_u, $(= \Delta u/\sigma_v)$, between 3 and 15 % at the end of the loading phase and recommends, as a starting value, a strain rate of 10%/hr for a MH material. In this study, strain rates of 1, 10, 20%/hr were evaluated.

3.1. General Consolidation Characteristics

The results of IL and CRS tests are presented in Figure 3 and the compressibility parameters summarized in Table 2. A total of 6 CRS tests were performed to evaluate the compressibility behavior of these residual soils. The results of the CRS tests were compared with those obtained in conventional IL tests, conducted on specimens trimmed from the same block sample. For consistency, similar stress ranges of σ'_v were chosen to develop the cycles of loading and unloading.

Despite differences in testing equipment and strain rates used in CRS tests, the obtained results indicate similar compressibility behavior in terms of compression index, C_c, and recompression index, C_r. For CRS tests, the average C_c-value was 0.425 for site 1, and 0.295 for site 2, with standard deviations of 0.09 and 0.02, respectively. The average C_r-value was 0.051 for site 1 and 0.027 for site 2. C_c and C_r-values computed from CRS tests are between -6% and 16% of those computed from IL tests. According to Kulhawy and Mayne [19], the grade of compressibility of the residual soils tested here, expressed in terms of C_c, is moderate to intermediate. The average decreases in void ratio for all tests was 0.356 and 0.311, for site 1 and site 2, respectively, over a vertical stress range from 1 kPa to 2440 kPa.

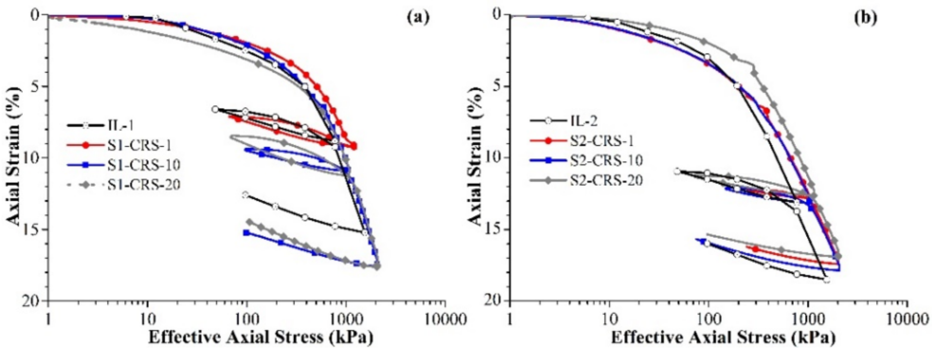

Figure 3. Axial stress-strain behavior from IL and CRS tests: a) Site 1; b) Site 2.

Table 2. Summary of compressibility parameters.

Specimen ID	C_r	C_c	σ'_y [a] (kPa)	$R_{u\text{-}max}$	AOCR [b]
IL-1	0.0515	0.400	480	-	4.36
IL-2	0.0310	0.353	235	-	2.63
S1-CRS-1	--	0.327	440	2.35	4.00
S1-CRS-10	0.0441	0.488	475	1.11	4.32
S1-CRS-20	0.0586	0.460	500	7.70	4.55
S2-CRS-1	0.028	0.282	260	2.70	3.25
S2-CRS-10	0.028	0.285	280	3.90	3.50
S2-CRS-20	0.024	0.318	300	4.35	3.75

[a] Based on the energy approach [27].
[b] Apparent Overconsolidation Ratio.

3.2. Strain Rate Effects during CRS Testing

CRS test results were interpreted based on the nonlinear theory proposed by Wissa et al. [20]. Figure 4 presents the variation, during the initial loading, of the u_b, hydraulic conductivity, k, coefficient of consolidation, C_v, and volume compressibility modulus, M_v. The values of k vary from 1×10^{-6} to 1×10^{-9} m/s, consistent with those reported by Terzaghi and Peck [21] for inorganic silts. The results also show that the magnitude of u_b depends on the strain rate and hydraulic conductivity [13]. As expected, for faster strain rates, higher u_b-values were measured. The C_v and M_v responses show a continuous decrease as the stress level increases. The values of C_v and M_v tend to converge for σ'_v larger than 600 kPa. Strain rate effects were not identified in the test results indicating that faster strain rates, with substantial time and cost savings, can be used to characterize this type of soils.

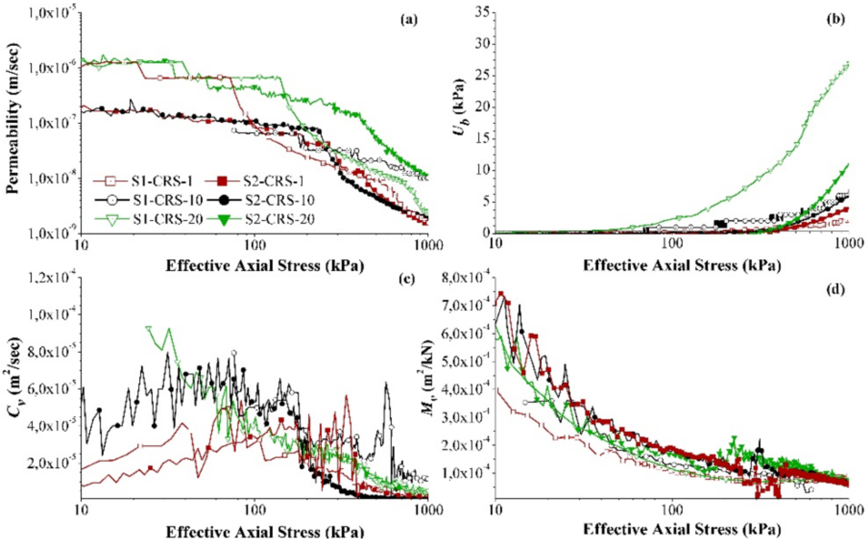

Figure 4. Consolidation properties during CRS loading stage: a) Permeability, b) Base excess pore water pressure; c) Coefficient of consolidation; and d) Volume compressibility.

3.3. Yielding Stress

Geological studies of the sites where the samples were retrieved indicate that it is unlikely that these soil deposits have ever been subjected to pressures significantly larger than their present overburden pressures. Wesley [22] and Mayne and Brown [23] proposed for residual soils the term Apparent Overconsolidation Ratio (AOCR) to differentiate the mechanism of consolidation of these soils to the transported soils. For sites 1 and 2, the AOCR were approximately 2.63 and 4.55, respectively (see Table 2), indicating that these soils are heavily overconsolidated (i.e. AOCR > 2.5). Several investigators [24-26] have concluded that the AOCR is due to the loss of unit weight during the weathering process, causing vertical unloading comparable to overconsolidation of transported soils, and bear no relationship to stress history [22].

Table 2 also lists the yield stress, σ'_y, estimated based on IL and CRS tests. The work per unit volume criterion proposed by Becker et al. [27] was used to determine σ'_y for all tests. In site 1, for CRS and IL tests, σ'_y is in the range of 440 to 480 kPa, with an average value of 471 kPa. Despite Ru-values lower than those specified in ASTM D4186 [13] were obtained for strain rates of 1 and 10%/hr, the variation in σ'_y was under 8% with respect to IL Tests. For site 2, CRS tests tend to overestimate σ'_y by 6% and 22% with respect to the estimated values based on IL tests. This difference may be related to the higher degree of weathering of site 2 as indicated by the presence of muscovite in the XRD analysis [28].

In general, σ'_y-values tend to increase for higher loading rates. Note that σ'_y-values computed for CRS tests conducted at 1%/hr are between 13% and 16% smaller than those computed for strain rate of 20%/hr. Similar strain rate dependency was observed by Leroueil S. et al. [29] for Champlain Sea clays, Nash et al. [30] for soft clay from Bothkennar, and Vaid et al. [31] for Leda Clays.

4. Conclusions

This paper presented the results of an experimental program designed to study the compressibility behavior of two residual soils formed by weathering of igneous-metamorphic basement under IL and CRS conditions. From the information presented herein, the following can be concluded:

- CRS testing provides continuous data readings that improve the definition of compressibility parameters with respect to conventional IL tests. The experimental results showed that C_c- and C_r-values computed from CRS tests are between -6% and 16% with respect to those computed from IL tests, even though pore water pressure ratios developed during CRS tests were lower than the reference values from ASTM D4186 for loading strain rates of 1 and 10%/hr.
- Strain rate dependency effects were observed for the yield pressure of residual soils. σ'_y-values computed for CRS conducted at 1%/h are between 13% and 16% smaller than those computed for loading strain rates of 20%/hr. The results suggested that σ'_y-values from CRS tests with a strain rate of 1%/hr and 10%/hr are comparable to those derived from IL tests, with a variation between −8% and 14%.
- Due to the high void ratios a rapid dissipation of excess pore pressures was observed indicating that CRS testing can be used to accelerate the completion of compressibility tests and definition of associated soil parameters. The practical implication of this result is that CRS tests with strain rates ≤ 10%/hr completed in less than 10 hours, provides similar compressibility parameters than a test performed under conventional IL conditions, completed in about a week.
- Strain rate effects were not observed in hydraulic conductivity, coefficient of consolidation and volume compressibility modulus, calculated using the nonlinear methods of ASTM D4186.

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