Proceedings of the 16th International Conference on Soil Mechanics and Geotechnical Engineering

doi:10.3233/978-1-61499-656-9-587

Yielding and stress-strain relationships for Bogotá clays

Relations de fluence et d'effort déformation des argiles de Bogotá

Jorge Alberto Rodriguez
Civil Engineering Department, Pontificia Universidad Javeriana, Bogotá, Colombia

ABSTRACT
Drained triaxial test results following load, unload and extension stress paths, as well as isotropic and Ko consolidation are used to identify the behavior of soft Bogotá clays. The intact drained strength and the critical state (CS) strength were obtained from the tests, as well as the volumetric compressibility, yielding and void ratio behavior at the critical state. The data is consistent with other natural clays reported in the literature, and provides the basis for a better understanding of the behavior of these soils for special projects in the city.

RÉSUMÉ
Les résultas d'essais triaxiales suivant des trajectoires d'effort de charge, décharge et extension, ainsi que de consolidations Ko isotropiques ont été utilisés pour identifier le comportement des argiles molles de Bogotá La résistance drainée intacte et la résistance de l'état critique (CS) sont obtenues des essais, ainsi que la compressibilité volumétrique, la fluence et le comportement de la relation de vides à l'état critique. Les résultas sont congruents avec les observations d'autres argiles naturelles rapportées dans la littérature, et ils fournissent une base pour mieux comprendre le comportement de ces sols pour des projets spéciaux dans la ville.

1 INTRODUCTION

The soils of the high plain where Bogotá is located are made of very soft lacustrine silts and clays in deposits that reach over 300 m deep encompassing deposits formed trough all the Pleistocene and Olocene. These very soft and compressible soils are challenging for the construction of foundation works in the city, especially for large excavations, especial structures and shallow large diameter tunnels for which no precedent exist in the city. A detailed analysis and design for this type structures is required based on numerical models. The elasto-plastic parameters required to properly model the behavior of these soils is studied by means of detailed laboratory tests. These parameters can be used as input for numerical models that can also be validated on existing projects where instrumentation data is available to extrapolate to the new projects for which no precedent exist.

Summary results of the study of stress – strain and yielding behavior of some of the softest of Bogotá clays are presented based on results of drained and undrained triaxial tests following different stress paths. Special attention is given to the non linear effects of shear and volumetric stiffness as a function of strain over a wide range of strain levels in drained conditions. These results are useful in understanding the behavior of these soils and of practical importance for the numerical modeling of special foundations, excavations and tunnels that are being designed and built in these soils, as well as for understanding long term behavior of existing structures.

The results show that these soft soils develop a relatively high intact strength, exhibiting a drained peak friction angle of 28 degrees with zero cohesion and a critical state (CS) friction angle of 13 degrees. The Ko value measured was around 0,75, consistent with the CS friction angle. The yield surface is well defined and is similar to the stress path followed by undrained tests in the normally consolidated (NC) state. The volumetric strains clearly define the deformability in the over consolidated and normally consolidated ranges with values of Cr and Cc which are consistent among different stress paths. The test results also show the location of CS line, parallel to the virgin compression line. The results are relevant to select appropriate parameters for elasto plastic models to be used for detailed analysis of complex structures and for understanding the long term behavior of existing structures.

2 SOIL CONDITIONS

Several soil samples were obtained in the north residential part of the city at a depth of 6 m using 63,5 mm diameter Shelby tubes in very close vicinity from each other. The soil in this area correspond to the more recent deposits of the lake located under a desiccated crust that shows slightly higher strengths and has some 4 m in thickness. The soils are very soft but its consistency increases slightly with depth down to 60 m where sand layers are found in the deposit down to some 200 m depth at the site. The estimated age of these samples is in the order of 20.000 years based on pollen analysis (Helmens, 1990, Hooghiemstra, 1984). The samples then correspond to the softest soils in the area and are relevant for the foundation of buildings in this residential part of the city.

Laboratory soil classification tests were conducted, including Atterberg limits, hydrometer particle size analysis and specific gravity. The soil corresponds to high plasticity clay (USC CH). Table 1 shows the soil classification data.

Table 1 – Soil classification data

Liquid limit	144
Plastic limit	48
Plasticity index	96
Specific Gravity	2,49
USCS	CH
Void ratio	2,73 - 3,01
Natural water content	110-123

3 LABORATORY TESTS

The samples were tested using a GDS 2HZ triaxial test apparatus at the Javeriana University in Bogotá. This system is capable of controlled stress, pore pressures or strain rate following different stress paths that can be programmed and controlled by the system (GDS, 1994). Samples 35 mm diameter by 70 mm height were trimmed from the Shelby tubes. The drained triaxial tests included isotropic and Ko consolidation, load, extension and tension tests. Additionally an undrained triaxial compression test was conducted on a normally consolidated sample after isotropic consolidation. The stress paths for the tests are shown in Figure 1.

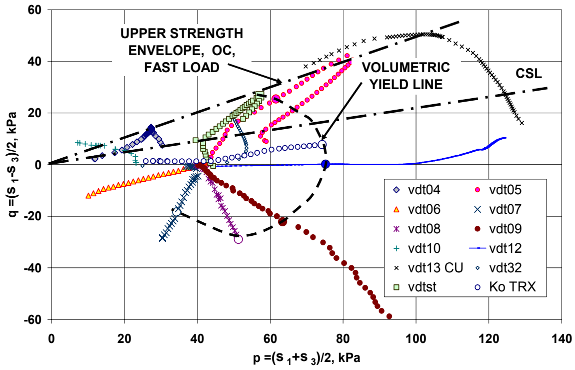

Figure 1 – Triaxial tests stress paths

The tests were automatically controlled by the system to be drained within a 10 kPa maximum pore pressure. The resulting test rates are shown in Figure 2. The test rate is important to consider due to the dependency of the fine soils response on strain rate.

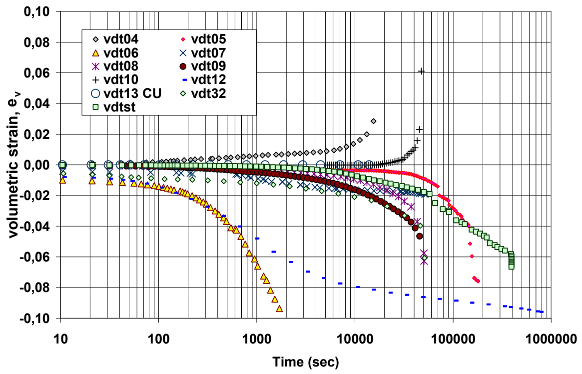

Figure 2 –Volumetric strain curves as a function of time

In Figure 1 the peak strength as well as the critical state line are shown. The results show a peak strength envelope with zero cohesion and a friction angle in the order of 28 degrees which was consistent with the strength developed by the sample in undrained conditions at a strain rate of 1,3E-5 (1/sec). This is a relatively high strength for this soft soil, but the results are consistent with the observed behavior of these soils, both in conventional triaxial tests and as deduced from the behavior of foundations (Moya and Rodriguez, 1987). Figure 2 show the strain rate in the tests and the increase in strain rate of the samples towards reaching the CS.

Figure 3 show the results of the deviatoric stress as a function of the axial strain. The data in the figure show the drained tests with mainly volumetric compression along with the tests with mainly deviatoric stress, and the compression test in undrained load. The data show that the drained compressibility is consistent for the tests in loading, unloading and tension. The deformation modulus, considering a secant modulus at 50% of the maximum deviatoric stress, is higher in shear, in the range of 1100 to 1700 kPa depending on the confining pressure, than in compression (500 kPa). Considering the formulation of Duncan and Chang (1970), that the variation of the secant modulus as a function of the ratio of the confining pressure to a reference value raised to an exponent m, the value of m obtained for the different confining pressures and measured modulus is 0,8.

The undrained modulus is higher, with a value of 5500 kPa for a consolidation pressure of 130 kPa. The shear stress-strain curve for undrained compression can also be approximated by an hyperbolic curve following the observation of Duncan and Chang. For the deformation modulus data obtained, taking into account the effect of confining pressure the undrained modulus could be calculated using elastic formulas using a poisson ratio of 0,29. This is important in the case of modified CAM clay type models that assume that undrained behavior can be represented using elastic parameters for stress states under the volumetric yield surface.

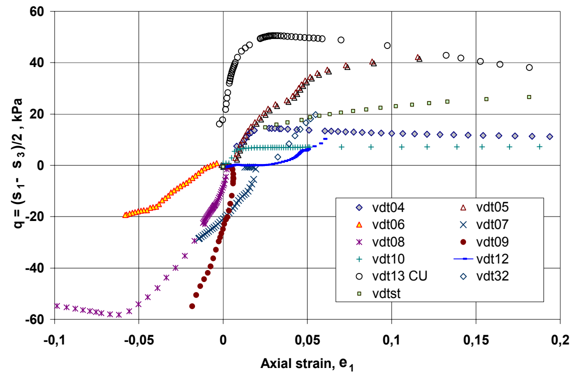

Figure 3. Deviatoric stress - strain curves

Figure 4 show the variation of the volumetric strain as a function of the axial strain. In the figure negative values of volumetric strain correspond to compression. All the samples underwent compressive strains in the order of 5% except for the two samples tested in extension and at the higher over consolidation ratios (test vdt04 OCR=2,5 and test vdt10 OCR=3). These samples showed dilatancy with strains in the order of 5% and 10% respectively. The samples vdt09 and vdt06 which were tested in tension had very large volumetric strains due to the type of test.

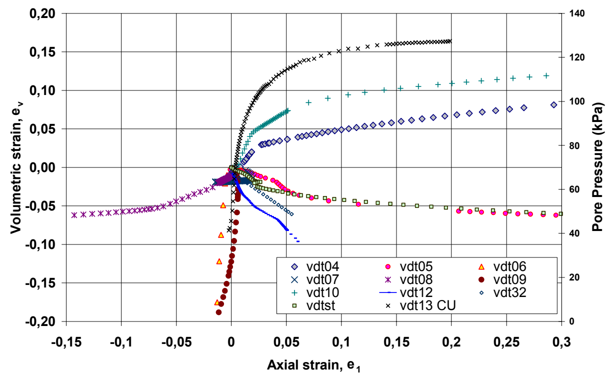

Figure 4. Volumetric strain – axial strain curves

The dilatance of the over-consolidated samples is significantly high since these soils samples were not so highly overconsolidated. The state of these samples is representative of the first few meters of the soft soils in the city which have been overconsolidated by dissecation. The results obtained are relevant for the short term excavations that are made for construction of basements and other buildings, but also for the permanent excavations made for channels. The soils initially show relatively high strength and the slopes are stable. With time and the movilization of strains the strength is reduced. Typical behavior of channel slopes in the city is a progressive degradation of stability with time, often over time spans of over 20 years.

Figure 4 also shows the pore water pressure generated in the undrained triaxial test. The pore pressures generated by the sample were high, with a value of 75 kPa when the sample first reached the strength line at a deformation of 0,8%, and kept increasing up to 120 kPa following the strength envelope . These values correspond to values of the parameter A of Skempton of A=0,75 at the peak and A=1,32 for the final state. The high increase in pore pressures indicate a strong rearrangement possibly collapse of the internal structure of this high void ratio soil.

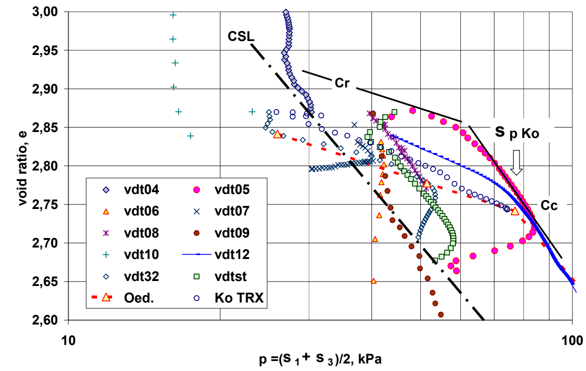

Figure 5. Void ratio – volumetric stress curves

Figure 5 show the variation of the void ratio for all the tests. The data in Figure 5 show consistent values of recompression (Cs=0,2) as well virgin compression (Cc=0,75) indices for both one dimensional and triaxial consolidation as well as for isotropic consolidation. All the samples tend to a unique primary compression line. The yield points are different for different tests and they define volumetric yield envelope shown in Figure 1. Also, all the samples tested in shear tend to the critical state line located as shown in Figure 5. The CS line is ostensibly parallel to the virgin compression line.

Crooks and Graham (1975), and Tavenas and Leroueil (1977) among others, have reported on the stress and yielding behaviour of soft natural clays. The results reproduced in Figure 6 show that the strength envelopes for natural NC clays is similar to the peak values obtained from Bogotá clay as shown in Figure 1. However. the large strain (CS) obtained for the Bogotá clay is significantly smaller.

The low strength at large deformations have an important serious implication for applications such as the use of driven piles which induce large strains in the soils. This type of piles has not been used frequently in the city because of the very low impedance made the driving inefficient. Diesel type hammers usually got stalled and gravity type hammers were also very inefficient. Recently hydraulic type hammers have been introduced to overcome this limitation. Traditionally mostly bored and cast in place piles have been used with good performance, although large concrete overrun from theoretical are common due to the high compressibility of the soils. These piles produce relatively small disturbance and work at low strains with respect to the surrounding soil. Driven piles are gaining acceptance and are being used to optimize the concrete quantities. These piles however produce very large strains and therefore can only mobilize the CS strengths that are significantly smaller. There is no adequate conscience of this fact and the driven piles are being designed assuming peak strength values.

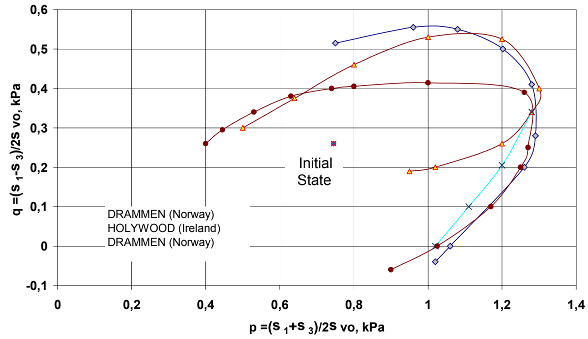

Figure 6. Yield and strength curves for other natural clays (Tavenas and Leroueil, 1977)

The shape of the volumetric yield surface is approximately elliptical centred around the Ko line. In the data shown in Figure 6, the Ko values are higher than obtained for Bogotá clay and therefore the elliptical shape is centred ed on a line significantly different from the isotropic compression line. For the Bogotá clay it could be said that the same trend is valid, but the initial state of this soil is closer to the isotropic state. From this point of view the traditional modified CAM Clay model would be more directly applicable for the Bogotá clay.

4 CONCLUSIONS

The results show that the soft soils of Bogotá develop a relatively high intact strength, with a drained peak friction angle of 28 degrees with zero cohesion and a critical state (CS) friction angle of 13 degrees. The volumetric yield surface is well defined and is similar to the stress path followed by samples under undrained loading in the normally consolidated (NC) state. The shape is approximately elliptical centered on the isotropic compression line. The volumetric strains clearly define the deformability in the over consolidated and normally consolidated ranges with values of Cr and Cc which are consistent among different stress paths. The test results also show the location of CS line, parallel to the virgin compression line in the e-p plot. The results are relevant to select appropriate parameters for soil plasticity models to be used for detailed analysis of complex projects and for understanding the long term behavior of existing structures, particularly channel slopes and for the design of driven piles.

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