Stress-strain behavior of a residual soil profile from gneiss

Comportement contrainte-deformation d'un profil du sol résiduel de gneiss

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ABSTRACT
This paper deals with the stress-strain behavior of mature and young soils of a typical residual soil profile from gneiss, as found in Viçosa - MG, Brazil. It is shown that the shear strength of saturated soil, both mature and young is independent of shearing direction. However, the visually more homogeneous mature soil showed to be more anisotropic, regarding the deformability, than the young residual soil that visually seems to be heterogeneous. The cohesion intercept tends to increase with soil suction according to a non linear relationship that can be adjusted through a hyperbolic function, while the angle of shearing stress was not influenced by soil suction. The yield curve of young soil was found to be fairly predicted using modified Cam-Clay model for saturated and unsaturated conditions. It is centered along the hydrostatic axis of stress and its shape did not change during saturated soil strain hardening that was obtained by joining the points to that exhibited the same plastic work and also did not change with increase soil suction.

RÉSUMÉ
Ce papier traite du comportement contrainte-deformation de sols matures et jeunes d'un profil typique du sol résiduel de gneiss, fréquemment trouve dans la region de Viçosa - MG, Brésil. Il est montré que la force du cisaillement de sol saturé, mature et jeune est independante de direction de la taille. Cependant, le sol mature visuellement plus homogène a montré être plus anisotropique, concernant le deformation, que le sol résiduel jeune qui visuellement paraît être hétérogène. La cohésion a tendance à augmenter avec succion du sol d'après une relation non linéaire qui peut être ajusté à travers une fonction hyperbolique, pendant que l'angle de frottement n'a pas été influencé par la succion du sol. La courbe de plasticitè de jeune sol peut être bien prédite avec le modèle Cam-Clay modifié. Sa courbe est centrée le long de l'axe hydrostatique de contrainte et sa forme n'ayez pas changé pendant durcissement du sol qui a été obtenu en joignant les points avec le même travail plastique et aussi n'a pas changé avec l'augmentation de la succion du sol.

Keywords : residuals soils, saturated behavior, unsaturated behavior, yield curve.

1 INTRODUCTION

The structure of residual soils mainly results from the weathering processes by which these soils are formed. Due to the degree of weathering, some residual soils do not keep the characteristics of the parent rock, whereas others residual soils are deeply influenced by the inherited discontinuities of the parent rock.

Due to anisotropy, the strength and deformation characteristics of the residual soils are dependent of the shearing loading direction. There are two basic types of anisotropy: inherent and induced. In the first case, anisotropy is due to a preferential particle orientation of the soil originated during the formation process of the deposit. Whereas, induced anisotropy is a direct consequence of the previous state of stress that the deposit was submitted after its formation. Intuitively, due to heterogeneity, it should be usual to expect an anisotropic behavior for residual soils, particularly when it is a saprolitic young residual soil, where, for instance, foliation planes are visible.

As far as the shear strength of unsaturated soils is concerned it is known today the dependence between shear strength and matric suction. This dependence is non-linear as shown by Escário & Saez (1987) and Fredlund et al (1987), among others. Many authors have proposed different empirical formulations to relate shear strength to matric suction. For instance, Röhm & Vilar (1995) presented results of triaxial tests carried out in a undisturbed sandy colluvium soil and adopted a hyperbolic relation between shear strength and matric suction.

Equations 1 and 2 show, respectively, the yield curves of the modified Cam-Clay model, for saturated soils and of the model of Alonso et al (1990), for unsaturated soils.

$$q^2 - M^2.(p_o.p - p^2) = 0 \quad (1)$$

$$q^2 - M^2.(p + p_s).(p_o - p) = 0 \quad (2)$$

In these equations, p is the net hydrostatic stress, q is the deviatoric stress, M is an inclination of the projection of the critical state lines (CSL) in the space (p; q) and p_o is the net isotropic pre-consolidation stress of the soil for a given suction value.

This paper deals with the stress-strain behavior of two horizons of a residual soil from gneiss. The influence of anisotropy in the shear strength and deformability of both soils was verified and special attention is paid to the aforementioned topics for the soil at unsaturated state and also for the yield curve of young soil under saturated and unsaturated conditions.

2 SOILS STUDIED

The soil samples were collect from a typical gneiss residual soil profile from the region of Viçosa (MG), Brazil.

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The upper layer (around 6 meters thick) is composed of completely weathered material and seems by visual inspection to be uniform and homogeneous. This layer is a mature residual soil, according to Vargas (1953) and corresponds to horizons IA and IB under the system of classification of Deere & Patton (1971). The many pedogenetic processes that acted on it has originated a red-yellow latosol that may be identified as sandy silt clay, with LL = 68 %, PI=29% and γ_s = 27.2 kN/m^3. The average physical indices of this soil, γ, w, S_r, e, respectively, were: 16.7 KN/m^3, 26.5 %, 68 % and 1.06.

The layer subjacent to the mature soil can be classified as residual young soil, according to Vargas (1953) or a saprolite (horizon IC) according to Deere & Patton (1971). It presents stratifications and features typical of the mother-rock, which can be easily identified. The visual inspection suggests that it might be a heterogeneous and anisotropic soil. Despite the appearance of rock, this soil can be easily destroyed when handled. It is a sandy silt soil, with LL = 38 %, LP = 23 %, IP = 15 % and γ_s = 26.7 kN/m^3. The average physical indices of this soil, γ, w, S_r, e, respectively, were: 17.8 KN/m^3, 17.86 %, 62 % and 0.77.

3 TESTING PROGRAM

The testing program consisted of drained triaxial tests on undisturbed samples of mature and young residual soils. These samples were obtained at 4 m depth and 12 m depth in a exposed slope in the aforementioned soil. The specimens were saturated by back pressure and subjected to conventional axial compression tests (AC), stress-path tests and isotropic compression tests. The mature soil was sheared applying the deviator stress in the vertical and horizontal directions. The young residual soil was also loaded in the vertical directions and in the directions normal and parallel to the schistosity as shown in the Figure 1. The effective confining pressures varied between 50 and 400 kPa.

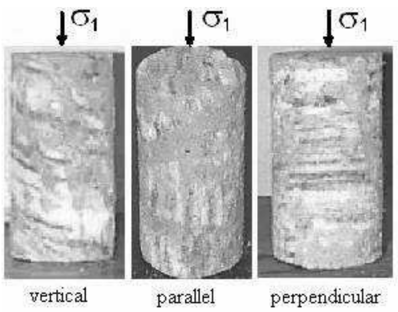

Figure 1. Directions of loading of the young residual soil.

Triaxial compression tests with matric suction control were also performed applying the axis translating technique (Hilf, 1956) to impose the matric suction (u_a-u_w), where u_a and u_w are, respectively, the pore air and water pressures. These tests were performed using a Bishop Wesley stress path cell with internal transducers for measuring displacements (radial and axial). The matric suction values (u_a-u_w) chosen for the tests were 40, 80, 160 and 320 kPa and the net confining stress values ($\sigma_c - u_a$) were 50, 100 and 200 kPa.

Some triaxial compression tests following distinct stress paths were also performed in the young residual soil. In these cases, saturated samples were consolidated at a stress of 150 kPa and afterwards sheared under different stress paths, as shown in Figure 2. In this same soil, hydrostatic compression tests were carried out for different suction values.

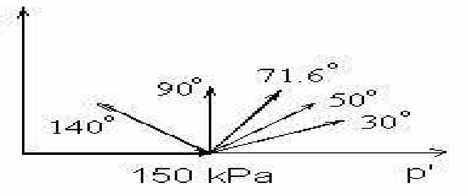

Figure 2. Stress paths followed in triaxial tests.

4 TEST RESULTS AND ANALYSES

4.1 *Saturated Soil*

4.1.1 *Deformability Analysis*

Table 1 presents values of elasticity modulus (E_{50}) and Poisson's coefficient (υ) obtained for both soils at stress level corresponding to 50% of the failure stress. It can be observed, in this table, that tests with different shearing loading directions performed with the young residual soil presented values of E and ν, practically constant, therefore indicating that this soil behaves isotropically. On the other hand, for the mature residual soil, tests with different shearing loading directions presented values of E and ν quite variable, therefore indicating an anisotropic behavior.

Table 1. Effect of Loading Direction on the Deformability.

Residual soil	Confining pressure (kPa)	E_{50} (MPa)	ν_{50}
Mature vertical direction	50	10.65	0.15
	100	14.16	0.08
	150	7.66	0.19
	200	11.70	0.12
	250	24.72	0.15
Mature horizontal direction	100	9.80	0.20
	200	6.66	0.21
	250	5.92	0.24
Young vertical direction	50	8.10	0.20
	150	13.60	0.18
	200	17.60	0.14
	250	....	....
	400	17.60	0.12
Young parallel direction	50	7.20	0.25
	150	14.80	0.20
	200	.....	......
	250	16.10	0.13
	400	13.80	0.17
Young perpendicular direction	50	7.20	0.25
	150	18.20	0.19
	200	......	......
	250	18.80	0.14
	400	16.40	0.17

The initial yield points in isotropic compression, conventional triaxial and stress path tests were determined using the approach suggested by Graham et al (1983).

Figure 3 shows the fitting of the yield curve of the Cam Clay model (equation 1) to the experimental data of the saturated young soil. The coefficient of determination obtained was R^2 = 0.88. In this fitting a value of M=1.20 was adopted, corresponding to a friction angle of 30^o, which was calculated from the saturated triaxial test results considering a null cohesion intercept. The value of p_o used (265 kPa) was obtained from the saturated hydrostatic compression test.

Figure 4 shows the hardening strain that was obtained by joining the points to that exhibited the same plastic work. The hardening parameter adopted was the one proposed by Lade & Kim (1988).

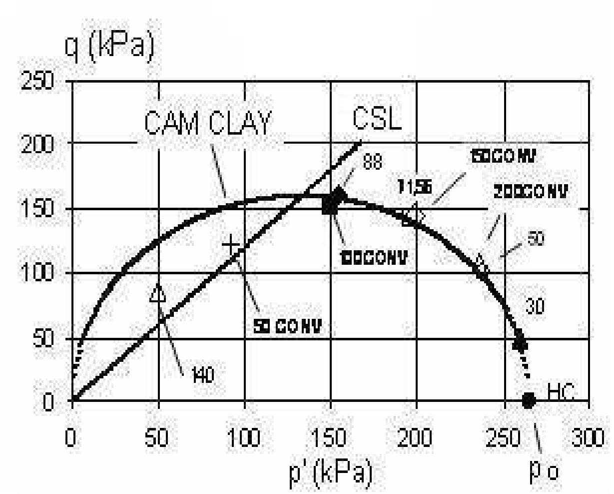

Figure 3. Equation 1 fitted to experimental data of saturated young residual soil.

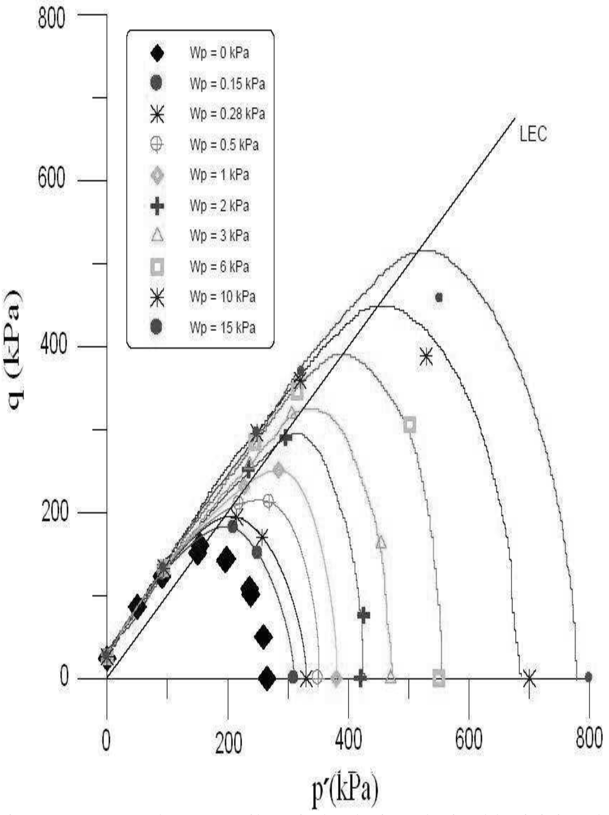

Figure 4. Saturated young soil strain hardening obtained by joining the points to that exhibited the same plastic work.

4.1.2 *Shear Strength*

Table 2 presents the values of cohesion (c') and angle of shearing resistance (ϕ') found for both soils tested (mature and young). It can be seen, that θ' does not change significantly, whereas cohesion varies slightly with the loading direction.

As the shear strength parameters did not vary much with the direction a unique shear strength envelope was adjusted for each soil. Figure 5 and 6 present the failure envelope obtained for the mature soil and for the young soil, respectively. For the mature soil, c' is equal to 15 kPa and ϕ' is equal to 31^0. For the young soil, c' is equal to 17 kPa and ϕ' is equal to 29^0.

Table 2. Effective Shear Resistance Parameters of the studied soils.

Residual soil	Shear direction	c' (kPa)	ϕ' (°)
Mature	vertical	19.2	31.0
	perpendicular	9.5	30.0
Young	vertical	17.0	28.0
	perpendicular	19.4	29.0
	parallel	26.0	28.0

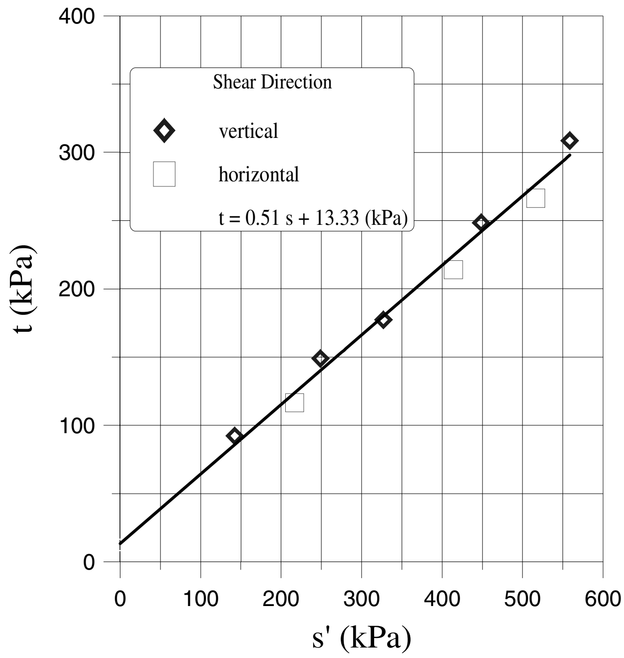

Figure 5. Shear strength envelope considering all the shearing loading direction. Mature residual soil. In this figure: $t = (\sigma_1-\sigma_3)/2$ and $s' = (\sigma_1'+\sigma_3')/2$.

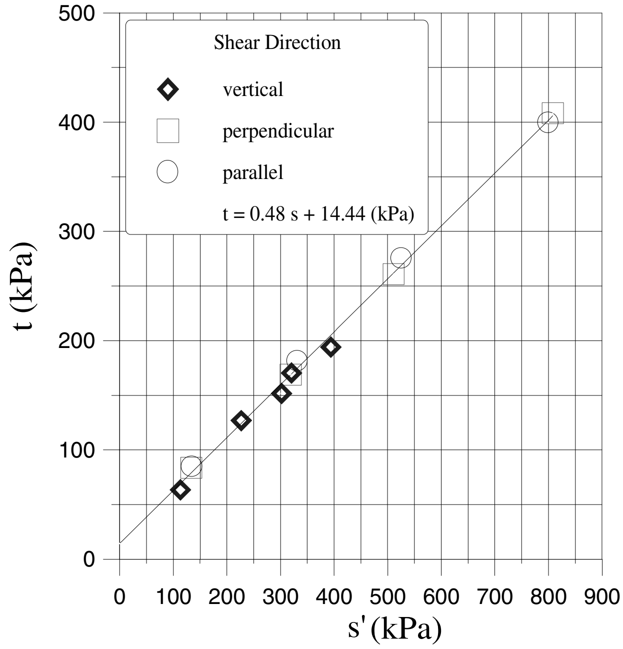

Figure 6. Shear strength envelope considering all the shearing loading direction. Young residual soil.

4.2 *Unsaturated Soil*

4.2.1 *Deformability Analysis*

The suction control tests aimed to determine the yield curves of non-saturated and compare them to the curve adopted in the model of Alonso et al (1990).

Figure 7 shows the variation of the yield curves with suction, for the tests conducted with constant suction values, equal to 0, 80, 160, and 320 kPa.

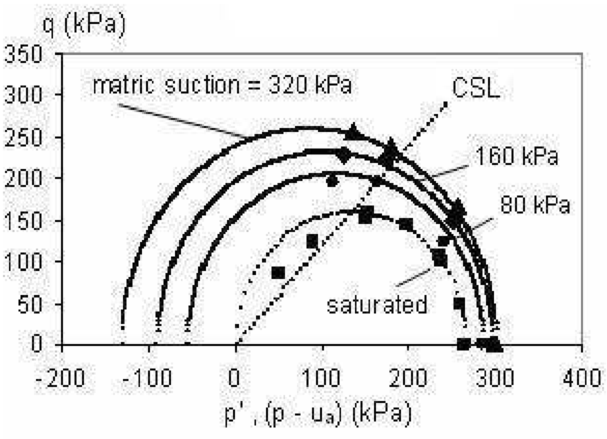

Figure 7. Yield curve variation with suction.

4.2.2 *Shear Strength*

Table 3 shows the shear strength parameters obtained for the both residual soils under unsaturated soil condition.

Table 3. Shear strength parameters.

Residual soils	u_a-u_w (kPa)	c (kPa)	ϕ (graus)	R^2
Mature	0	19.2	31.0	0.998
	40	41.2	31.0	1.000
	80	55.4	31.0	1.000
	160	82.4	31.0	1.000
	320	125.9	31.0	1.000
Young	0	24.0	28.0	0.993
	40	40.8	28.3	1.000
	80	57.6	28.3	0.999
	160	83.1	28.4	1.000
	320	98.5	28.0	0.999

As can be seen, the points representing failure allowed a good linear fit with R^2 close to 1, regardless of the suction adopted. Another interesting feature is that the shear strength envelopes are almost parallel, indicating that the friction angle (ϕ) does not vary with suction for both soils.

The whole variation in shear strength can be credited to the variation of cohesion with suction as shown in Figure 8, for both soils. The relation between shear strength and matric suction (u_a-u_w) is observed to be non-linear. The cohesion intercept tends to initially increase faster with suction and then the increases at a slower rate, as suction increases. To fit experimental data a hyperbolic function was chosen through Equation (3) as suggested by Röhm & Vilar (1995):

$$c(\psi) = c' + \psi/(a + b.\psi) \qquad (3)$$

In this equation, c (ψ) is the intercept of cohesion for a given suction value, c' is the effective soil cohesion, obtained from saturated tests or $\psi = u_a - u_w = 0$, and a and b are soil fitting parameters. Table 4 presents the soil parameters obtained from the fitting of Equation 3 to the experimental data.

Table 4. Values obtained in the fitting of the hyperbolic function to the experimental data.

Residual Soil	c'(kPa)	a	b	R^2
Young	24	1.86	0.0072	0.94
Mature	19.2	1.80	0.0039	0.95

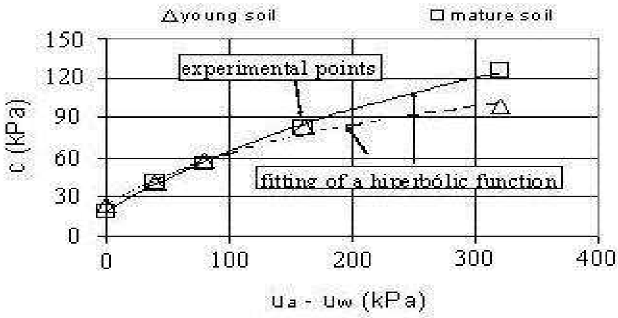

Figure 8. Variation of intercept of cohesion with matric suction (young and mature soils).

5 CONCLUSIONS

The young residual soil, in spite of presenting visible schistosity, has shown isotropic behavior with respect to both, deformability and strength. The mature soil that does not present any visible characteristic inherited from the parent rock and visually seems to be much more homogeneous than the young soil, behaved anisotropically.

It was verified for the two soils, that the internal friction angle almost did not vary with matric suction, and that the increase of the cohesion intercept with suction may be represented by a hyperbolic function.

The yield curve obtained for the saturated young soil has such a shape that it can be represented reasonably well by the yield curve adopted in the models derived from the mechanics of critical state soils (modified Cam-Clay) and also does not seem to alter with the strain hardening of the soil. As presented, however, these curves tend to overestimate the peak shear strength value of highly pre-consolidated samples. The yield curve format does not seem to alter with increase of matric suction and may be represented by the yield curve equation of the model of Alonso et al (1990), regardless of the suction adopted.

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