Influence of surface coverage on non saturated flows
Influence du revêtement de surface sur les ecoulements non saturé

F.A.J.P. Franch
Franch Engenharia e Consultoria de Fundações, São Paulo, Brasil
Universidade de São Paulo, São Paulo, Brasil
M.M. Futai
Universidade de São Paulo, São Paulo, Brasil

ABSTRACT

Data collected during an 8 month continuous measurement of rainfall, groundwater level and pore-water pressure for two portions of an unsaturated slope, in São Paulo, Brazil, under two surface coverage: vegetation and mortar; was analyzed to evaluate the magnitude and time-dependence behavior of these variables. Laboratory and “in situ” testing’s were performed to obtain physical, geotechnical and hydraulic characterization of the two geological/geotechnical horizons found on the slope. The ground smoothing caused by concrete application reduced rainwater infiltration into the soil, increasing the *run-off* and keeping active the suction during rainy periods, at most of the experimental slope. During the drought periods, the evapotranspiration promoted significant reductions in water pore-pressure in the vegetal slope portion, which not occurred in the concrete slope portion. There were "fast" variations of water pore-pressure in the clayey soil.

RÉSUMÉ

Les données recueillies au cours de 8 mois de mesure en continu de la pluviométrie, niveau des eaux souterraines et de la pression de l'eau aux pores dans deux portions d'une pente non saturée, à São Paulo, Brésil, dans le cadre de deux revêtements de sol, végétation et béton; sont analysées pour évaluer la magnitude et la dependence du temps de ces variables. Des évaluations laboratoires et "in situ" ont été réalisées pour obtenir une caractérization physique, géotechnique et hydraulique des échantillons intacts des deux horizons géologiques / géotechniques trouvés sur le remblai. Le terrain de lissage causés par l'application concrète des eaux de pluie réduit l'infiltration dans le sol, l'augmentation du ruissellement et de maintien de la succion active au cours de périodes de pluie, tout au plus expérimental de la pente. Au cours des périodes de sécheresse, l'évapotranspiration de promouvoir des réductions importantes dans de l'eau des pores-pression dans la partie végétale de pente, ce qui n'était pas survenu dans la portion de pente en béton. Il y avait "rapide" des variations de l'eau des pores pression dans le sol argileux.

Keywords : unsaturated soil, non saturated flow, suction monitoring

1 INTRODUCTION

In recent years, academic studies have expanded the knowledge about soil behavior under unsaturated conditions. Research involving this kind of soil, very common in Brazilian slopes, can contribute to promote innovations on landslides prevention field. From 2005 to 2007 were reported in brazil (www.estadao.com.br) 210 landslides that caused 92 deaths, 45 serious injured people, 98 destroyed homes, 1,600 homeless people, eight temporarily blocked highways, eleven partially blocked roads and a blocked tunnel. There are great challenges for geotechnical engineers regarding the landslides prevention and remediation on unsaturated soils.

This paper presents the results of experimental unsaturated slope monitoring located in São Paulo/SP, Brazil. It was object of study the influence of rainfall over the pore-water pressure variation; behavior comparison between a clayey soil and a silty soil; and two types of surface coverage: vegetation and mortar. It also presents results of “quick” changes over water pore-pressure.

This paper also will present the experimental field description, where were installed pluviometer, water-level meter and tensiometers; the main results involving the characterization tests and the hydraulic parameters determination at the local soil; and the monitoring results analysis.

Pore-water pressure variations in the soil affect the slopes stability on unsaturated soils. Scientific studies have established a relationship between the water rain infiltration (unsaturated flow) and the outbreak of landslides because of suction reduction and the increase of pore-water pressure under the soil. This process contributes to reduce the effective stress and therefore the shear strength of the soil.

The study of unsaturated flow is important to understand the pore-water pressure variation under the soil and the slopes stability. The equations for non saturated flow proposed by Fredlund and Rahardyo (1993) uses the following formulations as hypothesis: the Continuity Equation, Consolidation Theory, and Constitutive Relation of an Unsaturated Soil, associated to Darcy's Law, and they can be used to describe the water and air flows in unsaturated soils considering the volume variation in a porous system.

2 EXPERIMENTAL FIELD DESCRIPTION

The experimental slope is approximately a 15 m height, with 28 degrees of inclination, 40 m long and 16 m wide. There were two landslides near it in the last ten years (in 1998 and in 2004). At the southern portion of the experimental field the existing vegetation was substituted by a mortar layer with a medium thickness of 3 cm (in a 10m width lane); and, at the northern portion, the existing vegetation was maintained (in a 6m width lane), as shown in Figure 1.

The geological-geotechnical profile of the experimental slope has a red and white clayey layer, with 3m thick approximately, overlapping a portion of a reddish brown micaceous silty residual soil, as shown in Figure 2. There is an

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organic clay layer, with 20cm thick approximately, between the silty and the clayey horizons, indicating that is an embankment.

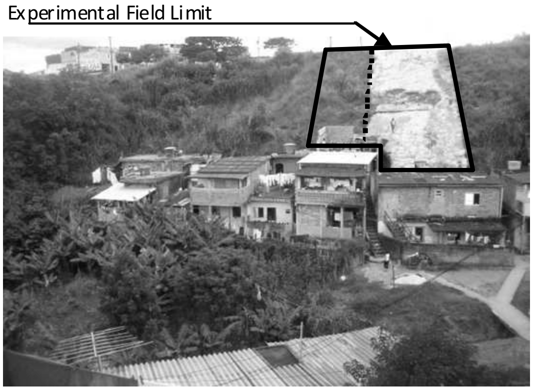


Figure 1: Experimental Field - Panoramic View

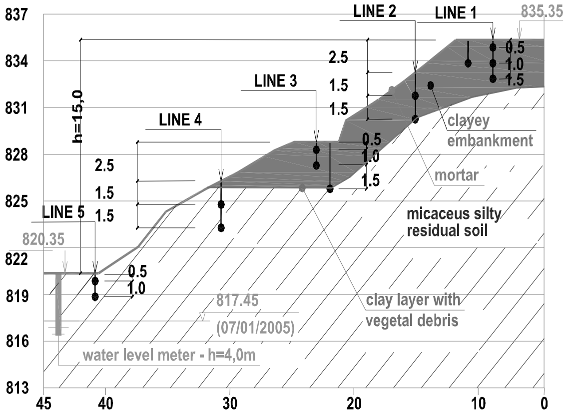


Figure 2: Geological-geotechnical profile and instrumentation used at the slope section coated with mortar: tensiometers and water level meter.

The used monitoring instruments comprised a 4 m deep water-level meter, built at the slope foot, that indicated water level table 2.9 m deep in early January 2005; a pluviometer installed about 50 m away from the experimental slope; and 25 tensiometers installed in two sections perpendicular to the level curves. The sections were located at the center of the vegetation and mortar covered areas, in five levels (lines 1 to 5), and three depths: 0.5 m, 1.5 m and 3.0 m, as shown in Figure 2. The vegetation covered area had 12 tensiometers, one less that the mortar covered area (at the slope top).

3 SOIL CHARACTERIZATION

Assays were performed for characterization and determination of hydraulic parameters using undisturbed soil samples from the clayey landfill and silty residual soil. The natural moisture of undisturbed sample of the earthen landfill, set aside in the rainy season of the year, is 20.6%, corresponding to a saturation level of 91.7%, very close to saturation, and the residual soil moisture, is 15.5%, corresponding to a saturation level of 52.6%, as shown in Table 1.

The natural specific weight of the clayey landfill, 20.5 kN/m^3, and its dry unit weight, 17.1 kN/m^3, are high and represent the typical values for a fine sandy lateritic compacted soil, according to Pinto's data (2002).

Both soils present a low void ratio and an expressive percentage of sand, about 40%. The embankment presents 42% of clay and the residual soil presents 53% of silt. The tested soils have low plasticity and compressibility, as shown in Table 2.

Table 1: Characterization tests

Material	w	Sr	γ_{nat}	γ_d	γ_s
-	(%)	(%)	(kN/m^3)	(kN/m^3)	(kN/m^3)
Clayey soil	20,6	91,7	20,5	17,1	27,5
Residual Soil	15,5	52,6	17,8	15,5	27,3

Where: w = moisture content, Sr = degree of saturation; γ_{nat} = natural unit weight, γ_d = dry unit weight; γ_s = solids unit weight

Table 2: Characterization tests

Material	e	w_L	w_p	I_P	Classif.
-	-	(%)	(%)	(%)	USCS
Clayey soil	0,60	43	29	14	ML/CL
Residual Soil	0,76	40	36	4	ML

Where: e = void ratio, w_L = liquid limit, w_P = plastic limit, IP = plasticity index

Laboratory tests were performed in order to determine the permeability coefficient of the clayey landfill, the silty residual soil and the mortar coating of the experimental slope.

The landfill has coefficient of horizontal permeability about 10 times greater than coefficient of vertical permeability, a typical feature of compacted soil. The residual soil has close values of coefficients of vertical and horizontal permeability and a 45^o angle permeability coefficient about five times greater than the coefficient of horizontal permeability. This result was explained considering that the soil presents a foliation plan making a 45^o angle with the horizontal. The laboratory results were confirmed by coefficient of permeability Guelph tests in the field, as shown in Table 3.

Table 3: Hydraulic characteristics of the material where the flow occurs

Material	k_{ver} (cm/s)	K_{hor} (cm/s)	$K_{45}{}^o$ (cm/s)	k_{guelph} (cm/s)
Clayey soil	2,2x10^{-7}	2,5x10^{-6}	-	2,0x10^{-7}
Residual Soil	1,2x10^{-4}	9,0x10^{-5}	4,5x10^{-4}	2,0x10^{-4}
Mortar	2,8x10^{-6}	-	-	-

The vertical permeability coefficient of the silty residual soil is greater than the vertical permeability coefficient of the mortar measured in the laboratory, which in turn is greater than the vertical permeability coefficient the clayey soil. So, the mortar must present a reduction effect over the rainwater infiltration into the silty residual soil, and should not affect significantly the infiltration into the embankment.

The water retention curves of the soils on the experimental slope were determined by laboratory tests including suction and pressure plates, and using filtering paper. The air entry value of the clayey soil is high, 150 kPa, and may indicate that this soil can be saturated most part of the year; otherwise, the air entry value of the residual soil is low, 4 kPa.

From the laboratory results, adjustments were performed over the retention curves and the suction variation was calculated according to the (volumetric moisture content), using mathematical equations proposed by Fredlund and Xing (1994), and that formulated by the van Genuchten (1980). In general the adjustments come close to the values obtained in the laboratory.

The adjustment constants a, n and m, according to Fredlund and Xing (1994) for the clayey soil are respectively 600, 0.867 and 1.355 and the saturated volumetric moisture content, θs, 61%. For the silty residual soil, the adjustment constants a, n and m are respectively 16, 1.315 and 0.763 and the saturated volumetric moisture, θs, 76%. The adjustment constants α, n and m, according to van Genuchten (1980), for the clayey soil, are respectively 0.007, 1.288 and 0.224. For the silty residual soil the adjustment constants α, n and m are respectively 0.067, 1.470 and 0.320.

The hydraulic conductivity functions of studied soils were obtained from analytical expressions developed by van Genuchten (1980) that are based on estimate model for relative permeability coefficient developed by Mualem. Comparing the hydraulic conductivity functions of studied soils, it was found that the silt hydraulic conductivity is greater than clay hydraulic conductivity for suctions less than 500 kPa and, for suctions greater than 500 kPa, the clay hydraulic conductivity is greater than silt hydraulic conductivity, as shown in Figure 3.

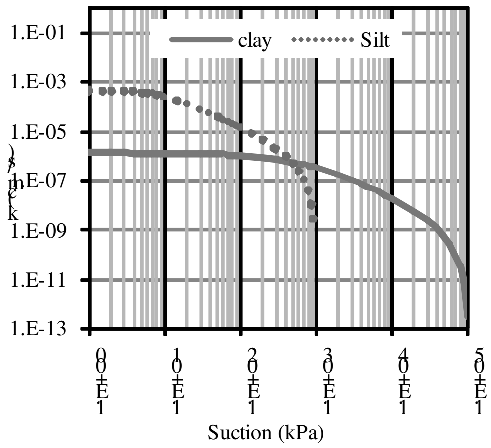


Figure 3: Hydraulic conductivity function for clayey landfill and silty residual soil, at a 45° angle.

It is not expected suctions greater than 500 kPa at field, as results of readings to be presented later in this work. This indicates that the silt must presents permeability greater than clay, at Field, throughout the year even during drought periods.

4 EXPERIMENTAL SLOPE MONITORING

The tracking period occurred from January to September 2005, over 261 days. From January to April (rainy season) the instrumental readings occurred daily, and weekly from May to September (period of drought), with the frequency of daily readings increased when heavy rain had occurred. The readings of pore-water pressure were taken using puntion digital tensiometers in tensiometric tubes, as described in Franch et al (2005).

The readings provided by tensiometers installed at two slope areas (covered with mortar and vegetation), at its 5 lines (1, 2 and 3 in clayey soil, and 3 and 4 in silty soil) and three depths (0.5, 1.5 and 3.0 m) presented consistent results with the rain quantity, and with the geotechnical and hydraulic characteristics of the soils.

The verified oscillations at water level followed the rainfall, as shown in Figure 4. The water level rose during rainy periods and fell when the rain stopped.

The analysis of nearly 1600 readings of pore-water pressure in the slope during the experimental period is shown through time series of pore-water pressure during the study period, in portions with mortar and vegetation in the line 3, located at 1.5 m deep.

The mortar covered area of the slope presented pore-water pressure of about 10 kPa lower than the vegetation covered area, during the rainy season (January to April) and the drought period (May to August). In September the vegetation covered area presented pore-water pressure lower than the mortar covered area, as shown in Figure 5.

The ground smoothing caused by mortar application reduced rainwater infiltration into the soil, increasing the *run-off* and keeping active the suction during rainy periods, at most of the experimental slope. During the drought periods, the evapotranspiration promoted significant reductions in pore-water pressure in the vegetation covered part of the slope, which not occurred in the mortar covered part of the slope. The mortar coating, more permeable that the clayey soil, did not work as an impermeable barrier.

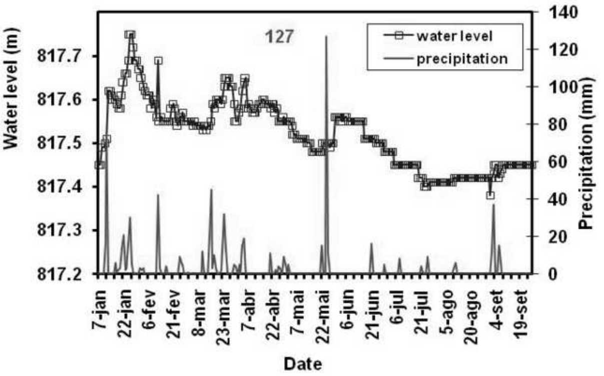


Figure 4: Water level x Rainfal

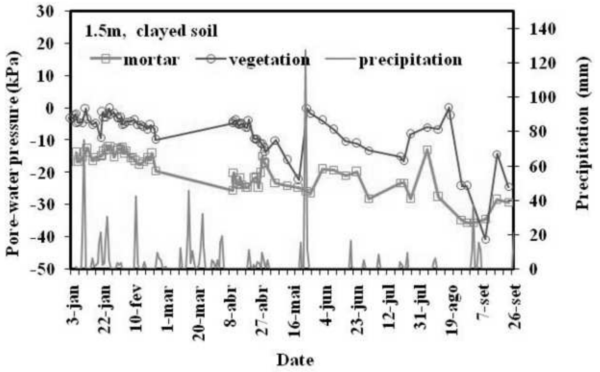


Figure 5: Time Series of pore-water pressure and rainfall at row 3 (mid-slope) in both surface slope covered parts at 1.5 m deep.

In a rain event occurred on May 24, when there was a precipitation of 127 mm, the pore-water pressure remained stable in the mortar covered part of the slope; and the vegetation covered part of the slope had increased pore-water pressures, from -22 to 0 kPa, at 1.5 m deep in the morning following the precipitation. There were "fast" variations of pore-water pressure, within short time interval between the rainfall and the pore-water pressure variation, considering the low hydraulic conductivity of the clayey soil. That must have occurred because, even the negative pore-water pressure, the clay remained saturated and the water pore-pressure variation did not require any flow.

In the Figure 6(a) are presented pore-water pressure profiles at the top of the experimental slope (line 1) in clayey soil and, in Figure 6(b), between the middle and the base of the slope (line 4) in silty soil, in the mortar covered part of the slope, from May 13 to July 3. In this period there was a 15 mm rainfall on May 21 and 127 mm on May 24. At the top of the slope, at 0.5 and 1.5 m deep, the pore-water pressure increased on the day following the 127 mm rainfall, reaching values close to the hydrostatic pressure; and in line 4, at 1.5 and 3.0 m deep, the pore-water pressure increased significantly only on July 3, nine days after the intense rainfall.

The results presented above indicate that the pore-water pressure variations in clay occurred more quickly than in the silty soil. This result seems to be unexpected, considering that the 45 degrees permeability coefficient (preferred flow direction) of clay, $1x10^{-6}$ cm / s, is 100 times smaller than the silty soil, $1x10^{-4}$ cm / s.

The results got at the experimental slope monitoring, pore-water pressure variation in 1 day at 1.5 m deep in clayey saturated soil, suggest that the "fast" pore-water pressure variations may be related to the pressure-water transfer. Another hypothesis, which cannot be ruled out, refers to the existence of cracks and fissures in the soil that would present coefficient of permeability greater than those measured in the laboratory. In the other hand, Guelph permeability tests made at field confirmed the laboratory results for both soils, reducing the possibility of the existence of those discontinuities.

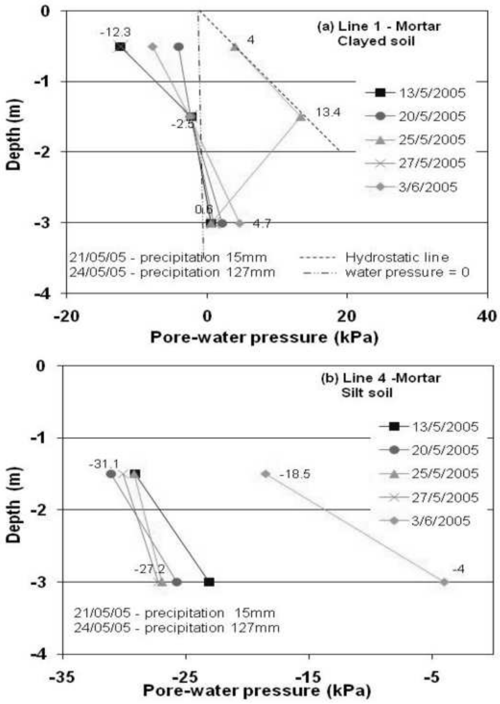
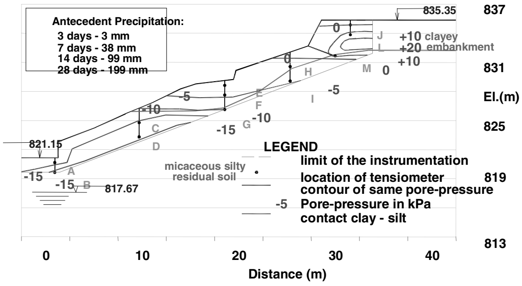


Figure 6: Pore-water pressure profiles during the drought period, from May 13 to June 3, in rows 1 (a) and 4 (b), with clayey and silty soil, respectively, and mortar coating

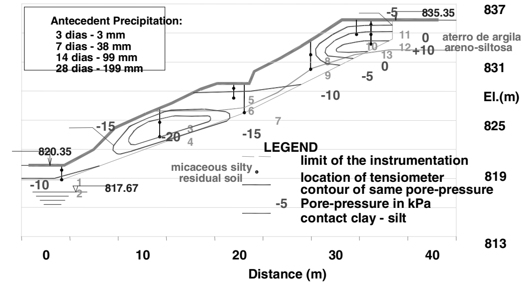
In Figure 7 are presented cross sections of the experimental slope showing the pore-water pressure distributions for mortar and vegetation covered areas, on February 1st, the rainy season when it was recorded the highest values of pore-water pressure during the monitoring tasks. The portion of the slope covered with vegetation presented pore-water pressure greater than the mortar covered portion, even in clayey soil, lines 1 to 3 (-5 to 20 kPa> -10 to 10 kPa), like in silty soil, lines 4 and 5 (-15 to -10 kPa> -20 to -10 kPa). This result was repeated during the rainy periods and was explained by the ground smoothing promoted by the mortar application and the infiltration reduction in silty soil coated with this material, with lower permeability.

Maybe the positive pore-water pressure values recorded in clayey soil are the outbreak factor for the landslides occurred (in 1998 and 2004) in the hillside where is located the experimental field. The mechanism that caused the suspended water table at the top of slope and the positive pore-water pressures may be associated with the anisotropy relative to the clayey soil permeability and to the organic clay layer located between the embankment and silty residual soil (possibly having lower permeability). The presented results confirmed the outbreak mechanism for landslides proposed by Vaughan (1985) in which saturation fronts could cause the positive pore-water pressures in case of soils with permeability decreasing with depth.

The silty soil presented water pore-pressures lower than clayey soil during all monitoring time, even the rainy period like the drought period. This result can be explained by: (a) more permeability of the silty soil, presenting more water flow into the mass because gradient of gravity potential; (b) relationship between the functions of soil permeability coefficient, resulting a silt permeability increasing throughout the year, considering the water pore-pressure ranges in the mass; and (c) inflow of air in the silt less than inflow of air in the clay, reducing the moisture of this soil and its respective water pore-pressure.



(a) Vegetation covered area of the slope, in 01/02/05



(b) Mortar covered area of the slope, in 01/02/05

Figure 7: Pore-water pressure distribution in the slope, on February 1st, in vegetation (7a) and mortar (7b) covered parts of the slope.

5 CONCLUSIONS

The verified oscillations at water level followed the rainfall. The ground smoothing caused by concrete application reduced rainwater infiltration into the soil, increasing the *run-off* and keeping active the suction during rainy periods, at most of the experimental slope. During the drought periods, the evapotranspiration promoted significant reductions in water pore-pressure in the vegetal slope portion, which not occurred in the concrete slope portion.There were "fast" variations of water pore-pressure in the clayey soil.

It may be related to the pressure transfer amid continuous aqueous, without water flow.

Maybe the positive values for water pore-pressure recorded in clayey soil were the outbreak factor for the landslides occurred (1998 and 2004) in the hillside, where is located the experimental field.

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