Mechanical behavior of a volcanic ash soil (Typic Hapludand) under static and dynamic loading

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Abstract

Andisols are often subject to landsliding and coinciding liquifaction of the existing soil structure because they dominate at steeper slopes and show often an insufficient hydraulic conductivity. Thus, soil erosion at those sites is considered as one of the major risk. In order to quantify the proportion of the mechanically and of the pore water dependent soil strength, we evaluated their dependency during compression (divergent process) and shear tests as a function of the pore water pressure in a volcanic ash soil (Typic Hapludand). Undisturbed samples collected at two depths (0–15, 40–55 cm) were equilibrated at two pore water pressure values (-60 and -300 hPa). Thereafter they were compressed for either 10 or 30 min, respectively at each total stress applied. Shear tests with a shear speed of 0.2 mm min^{-1} were performed at the same two initial pore water pressure values, after the samples had been statically pre-stressed with identical loads all smaller than 400 kPa. The pre-compression stress was similar between time intervals when the samples were dried at -60 hPa, but on average for the two depths the pre-compression stress was 32% lower when 30 min steps were performed because of a more complete settlement due to the time dependency of water flow during soil deformation. There was an increase in cohesion of 30% in topsoil and 900% in subsoil when the pore water pressure changed from pF 1.8 to pF 2.5.

Irrespective of the loading time interval, pore water pressure increased to even positive pore water pressure values when mechanical stresses of >300 kPa were applied, being more important in samples after pre-drying at -60 hPa than at -300 hPa. In the shear test the behavior was similar, but positive values of pore water pressure already occurred when the vertical stress exceeded 200 kPa. Thus, we can conclude, that hydraulic properties are specially important in soils showing thixotropic behavior and/or when shear stresses are applied resulting in a more pronounced weakening by increasing the destabilizing pore water pressure as a reason for an enhanced particle rearrangement and soil homogenization compared with the original soil structure.

Keywords: Pre-compression stress; Shear strength; Pore water pressure; Dynamic or static loading; Volcanic ash soil

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1. Introduction

When soils are loaded or ploughed, the air and water filled pores are affected, resulting in a reduction in the total volume of soil and changes in the pore size distribution, pore continuity and water saturation. Soil strength is the ability of soils to withstand mechanical loading (Horn, 1993) and depends on grain size distribution, kind and content of clay minerals and organic substances, structure, bulk density, pore size distribution and pore water pressure (Horn, 1988; Horn and Lebert, 1994). It quantifies mechanically based material functions. However, the mechanical behavior of a soil (volume change and shear strength) is highly sensitive to the kind of loading (static or shear forces applied) which is often demonstrated also by the efforts of agricultural engineers to reduce the draft force of agricultural tools by applying dynamic i.e. shear forces at the tool (Horn and Baumgartl, 2000). Thus, during loading, or plowing events but also by earthworm activity, plant root growth and trampling of livestock, total normal stress promotes the transmission of stresses via the solid (effective stress) and the liquid phase (neutral stress = pore water pressure). Both, effective and neutral stresses are consequently the result of internal and external forces (Baumgartl et al., 2000).

Based on the very specific mineralogy, Andisols, when completely dry, behave like fine sand; however, even if the soil seems to be dry, shearing e.g. by squeezing water out, results in a soil moistening, and the soil gets more slippery (Wright, 1965). This feature is often referred to as thixotropy (Warkentin, 1985) and it explains mass movements, due to either the gravity or animal trampling, known as soil erosion (De Noni et al., 1985). Such thixotropic behavior is the more pronounced when shear processes and not only compression occur because the mobilization of water is the more intense when a change in shape of a given soil volume occurs. Consequently, the hydraulic conductivity will be reduced drastically and finally leads to the lubrication of the soil.

In general, deformation of soil materials reflects changes in both shape and volume and is therefore a mixture of shear and compression (Kay, 1990). In unsaturated soils, there are many approaches to relate the stresses in a soil deformation process (Coleman, 1962; Barckley, 1971; Richards, 1974; Nearing, 1995), However, the mechanical description of the static and shear stresses applied is mostly referred to Bishop (1959) by the effective stress equation:

$$\sigma' = (\sigma - u_a) + X(u_a - u_w)$$

where the effective stress σ' depends on the total normal stress σ, the pore air pressure u_a, the pore water pressure u_w and the X factor, which depends on the degree of saturation of the soil, and takes values $X = 0$ at pF 7 and $X = 1$ in saturated soils, respectively (Horn, 1993).

Furthermore, we have to realize, that soil strength increases as long as the decrease in the negative pore water pressure exceeds the decrease in the X factor; in sandy soils, the highest strength value is obtained at less negative pore water pressure values compared to the behavior in clayey soils, owing to the smaller fraction of finer pores in the former one. Thus, each soil has a maximum strength at a certain pore water pressure that depends on the aggregation, pore size distribution and pore function (Horn et al., 1994).

When undisturbed unsaturated soils which already contain coarse and air filled pores are loaded and sheared, at first these coarse pores are diminished in diameter, which results in a more negative pore water pressure while the X factor increases. Consequently, the soil gets more stable (Horn et al., 1994). If, however, the external stress increases, the rearrangement of particles results in a higher degree of water saturation and finally results in convex water menisci, and a soil softening; the strength declines (shearing test) or the deformation increases (compression test). When the soil is finally completely sheared, the pore water pressure may become more negative again after stress release because of the expansion of the horizontally oriented soil pores (Gupta and Larson, 1982).

Depending on the hydraulic conditions of the soil, the dynamic character of a shear test should result in more positive pore water pressure values at lower stresses, as compared to the compression test. However, these interactions between particles or pore rearrangement depending on the kind and intensity of loading are seldom analyzed and the effect of coupled mechanical and hydraulic processes is not quantified. Thus, the object of this study was to evaluate the behavior of the pore water pressure under dynamic and static loading and its effect on the mechanical properties of soil materials derived from volcanic ash with different pedogenic evolution.

2. Materials and methods

Samples of a Typic Hapludand located in Osorno in the South of Chile, were collected at two depths, 0–15 and 40–55 cm, in a site under grass. Table 1 presents selected properties of this soil. The grassland is included in the rotation system with cereals with traditional management: applications of chemical fertilizers and manure plowed each 4–6 years and cattle grazing and trampling. The organic carbon content from the superficial layer is low in relation to the average of the typical soil, ranging between 94 and 134 g kg^{-1} (Beinroth et al., 1985; Mella and Kühne, 1985). Considering the same parent material, it is possible to find a sequence of pedogenetic development: the topsoil horizon has a good structure, with strong, fine and medium granular aggregates, while with depth the structure is incipient, with weak, coarse and medium sub-angular blocky and common cracks (Mella and Kühne, 1985).

The undisturbed samples were taken in cylinders of 10 cm diameter and 3 cm height, saturated and equilibrated at −60 and −300 hPa pore water pressure. Thereafter, the samples were analyzed in compression and shear tests.

2.1. Compression test

In the confined compression test (Kézdi, 1980), increasing normal stresses from 0 to 400 kPa were applied in a multistep equipment, recording the vertical deformation, the pore water pressure and the vertical stress. The pore water pressure was measured by a micro-tensiometer inserted in the soil sample from below. The response time is smaller than 20 s which results in a high resolution of pore water pressure changes with mechanical and hydraulic stresses applied. In order to evaluate the effect of pore water pressure on changes in strength and its effect on the interaction between particle mobility expressed as soil deformation and pore water pressure development, tests were performed at two time intervals between each step. Three replicates of each treatment (superficial and sub-superficial), two time intervals (10 and 30 min) and two initial pore water pressure values (−60 and −300 kPa), were measured. Based on the data of the vertical stress dependent soil deformation, the pre-compression stress value (Horn, 1981) was determined after Casagrande (1936).

2.2. Shear test

A frame shear box was used to perform the strain controlled shear tests (Kézdi, 1980), with normal stresses between 20 and 400 kPa and five replicates for each treatment. The test was performed under "$C_{10,30}D$ = consolidated for 10 and 30 min, respectively, and time dependent drained" conditions. During the shear test at a constant speed of 0.2 mm min^{-1}, the vertical soil deformation, changes in pore water pressure and shear strength were recorded. The pore water pressure was recorded with the same kind of micro-tensiometers used in the compression test. The low shear speed simulates the mass movement processes because of steep slopes and trampling of Andisols. The cohesion and angle of friction were derived, too (Fredlund and Rahardjo, 1993).

2.3. Other analysis

Water retention curve was determined by the pressure plate technique (Klute, 1986); bulk density

Table 1
Soil properties of a Typic Hapludand (Osorno Serie) at two depths

Horizon	Depth (cm)	Clay (%)[a]	Silt (%)[a]	Organic C (g kg^{-1})	Bulk density (Mg m^{-3})	Volumetric water content (%)	
						−33 kPa	−1500 kPa
Ap	0–15	39.1	50.9	59.0	1.0	52.2	28.8
BC	40–55	32.9	55.0	5.4	0.8	63.0	22.2

[a] After Mella and Kühne (1985).

was measured by core method (Blake and Hartge, 1986).

2.4. Statistical analysis

Basic statistical parameters were determined between the replicates. Analysis of variance was performed with $P < 0.1$, comparing soil properties among soil depths, pore water pressures and time intervals in the compression test. For the Coulomb's failure line, a linear regression analysis and the statistical significance were proofed.

3. Results and discussion

3.1. Time dependency of mechanical properties

The pre-compression stress value depends amongst others on the maximum previous pre-dessication, the maximum external load and the hydraulic properties of the soil during loading and it reaches higher values, if the samples are aggregated, or if the drainage off of excess soil water is prevented due to a smaller hydraulic conductivity, and/or due to a reduced pore continuity (Horn, 1993). In this way, a lower value of pre-compression stress is expected when the time interval during successive loads is longer, especially in fine textured soils. Nevertheless, in soils near saturation, the low hydraulic gradient could be more significant than the high hydraulic conductivity. Table 2 shows the values of pre-compression stress for each time interval.

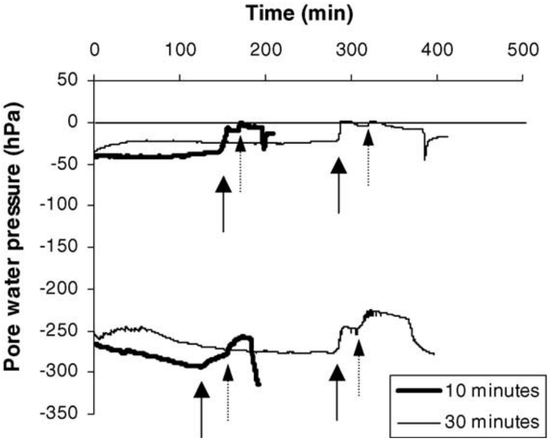

Fig. 1. Change in the pore water pressure during the compression test in samples with different initial pore water pressure and time intervals between load steps. Filled arrows, 300 kPa load step; dotted arrows, 400 kPa load step.

At −60 hPa pore water pressure, there were no important differences between time intervals, because the hydraulic gradient was low and final applied stresses resulted in neutral stresses (Fig. 1). In the soil material equilibrated at −300 hPa at the beginning of the test, the longer time interval ensured a more complete soil settlement for each load, resulting in a more complete pore decrease and smaller pre-compression stress values, compared with those of the 10 min intervals (Table 2). Nevertheless, there were statistically significant differences between time intervals only in 40–55 cm depth samples at initial pore water pressure of −300 hPa, caused by the high variability within the replicates, with coefficients of variation between 6% for the 30 min intervals and 30% in 10 min intervals. Neutral stress could explain the similar values of pre-compression stress in between the samples compressed at different initial pore water pressure values.

Irrespective of the initial pore water pressure, the samples from 40 to 55 cm showed higher pre-compression stress values than the topsoil samples,

Table 2
Pre-compression stress value (kPa) of the Osorno soil

Initial tension (hPa)	Time interval (min)	Pre-compression stress (kPa)	
		Ap (0–15 cm)	BC (40–55 cm)
−60	10	42 a A	80 ab B
	30	57 ab A	78 ab A
−300	10	70 b A	113 b A
	30	51 ab A	72 a B

Values followed by a different lowercase letter are significantly different in the column, values followed by a different capital letter are significantly different in the row (LSD, $P \leq 0.1$).

Table 3
Cohesion (kPa) and friction angle in Osorno soil evaluated at two pore water pressure values

Soil depth (cm)	Pore water pressure (hPa)	Cohesion (kPa)	Angle of internal friction (°)
0–15	−60	18.4 a	38 a
	−300	24.2 a	42 a
40–55	−60	3.0 a	36 a
	−300	32.3 b	35 a

At the same depth, values followed by a different letter are significantly different in the column ($P \leq 0.1$).

which is in agreement with the natural higher surcharge at that depth (Horn, 2002). Nevertheless, there were significant statistical differences between soil depths (LSD, $P \leq 0.1$) only in two of the comparisons, probably because of the high variability in the replicates.

With respect to the shear parameters, Table 3 presents the results of cohesion and friction angle derived from a linear regression analysis (Kézdi, 1974). The decrease in the matric potential from pF 1.8 to 2.5 without a strong slope change of the water retention characteristics resulted in a nearly identical increase in soil cohesion. The stronger increase of cohesion in subsoil samples due to desiccation, is expected in volcanic ash materials because with the aggregate development (0–15 cm samples), an increase in organic carbon content and with the allophan formation, the aggregates become stronger and less susceptible to water erosion, while the secondary porous system explains lower values of X factor, resulting in closer values of cohesion in the range of pore water pressure between pF 1.8 and 2.5.

3.2. Changes in pore water pressure under static and dynamic stress application

Under static loading, at any initial pore water pressure and time interval in between the applied mechanical stresses, there was a more pronounced change in the pore water pressure when a mechanical stress of 300 kPa or greater was applied. Fig. 1 shows this result for the sub-superficial sample, representative for both depths and all replicates. The change is the more pronounced for samples at less negative initial pore water pressure. If the samples were drier (initial pore water pressure −300 hPa), we observed smaller changes in the pore water pressure with increasing mechanical stress applied.

Under dynamic conditions (shear tests), normal stresses exceeding $\sigma_1 > 200$ kPa already resulted in positive pore water pressure values (Fig. 2), although the samples had been pre-equilibrated with the same mechanical stress beforehand without such an increase to even positive values. In addition, directly after the static stress application, there was a fast increase in the pore water pressure together with an intense height

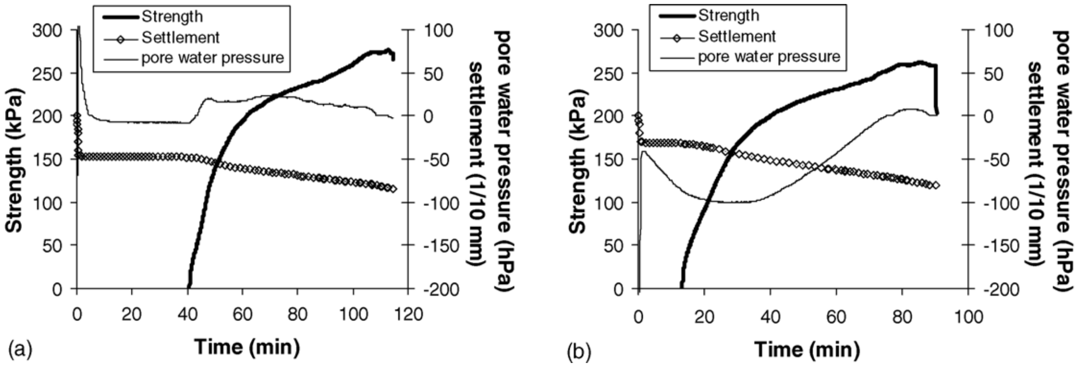

Fig. 2. Shear strength, settlement and pore water pressure changes during shear test for soils equilibrated initially at (a) −60 hPa and (b) −300 hPa at a normal load of 400 kPa.

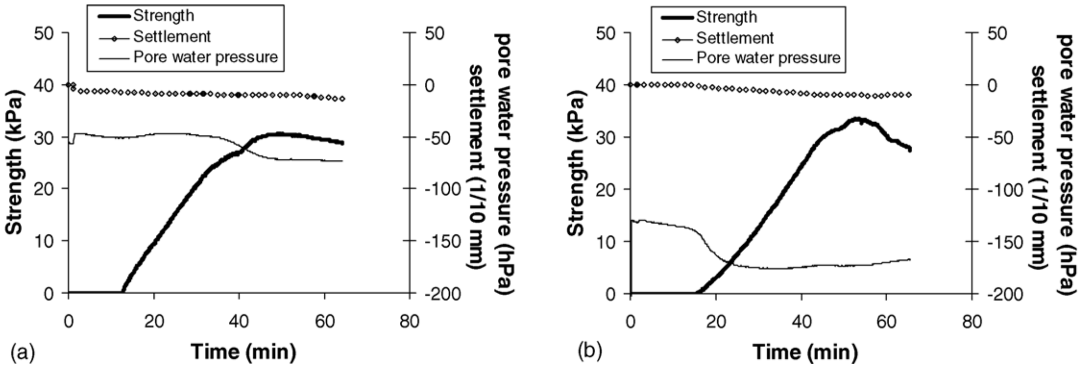

Fig. 3. Shear strength, settlement and pore water pressure changes during shear tests for soils equilibrated initially at (a) −60 hPa and (b) −300 hPa at a normal load of 20 kPa.

decline, but the change in pore water pressure became more negative again. The decline depends on the remaining hydraulic conductivity. It has to be stated that even if beforehand the final stress dependent equilibrium under static compression was reached, the shear process at the same vertical stress always resulted in a further pore water pressure generation, because shear causes a more pronounced rearrangement of particles, like a ductile deformation of loose sand materials (Kézdi, 1974; Mitchell, 1993) at the given small bulk density values (Table 1).

At low normal stresses (Fig. 3), the strain behavior of the soil was similar. The contrary trend became also more pronounced when the normal load was lower than 200 kPa during the shear test, as the pore water pressure became even more negative compared to the behavior when compressed. The decrease in pore diameter of the originally airfilled coarser pores coincided with a corresponding redistribution of water and a decrease in pore water pressure (Horn et al., 1994).

The critical normal stress can be either defined by the transition of the pre-compression stress range to the virgin compression behavior and or by the coinciding changes in the pore water pressure related to the applied mechanical stress. The critical normal stress was different for static and dynamic loading processes. In the compression test, more than 300 kPa had to be applied to create more pronounced changes in pore water pressure, while in shear test 200 kPa were sufficient to produce positive pore water pressure values at the end of the test. The dynamic stress application in the shear test causes a parallelisation of the pores in the shear plane and also affects the continuity of the porous system, decreasing the volume of soil and retarding the water redistribution. This explains why a lower mechanical load was needed to reach positive pore water pressure values. If we include all datasets, also a mechanical stress of approx. 300 kPa can be derived at the transition point but the standard deviation between the datasets of the static and of the dynamic loading is greater in the shear variant than in the compression one (Fig. 4).

If we finally calculate the effective stress at a given total stress under static and dynamic loading (Table 4), we can proof that shear stress application always results in a strength increase (strength hardening) if the pre-compression stress is not exceeded while in the virgin compression load range a soil softening results

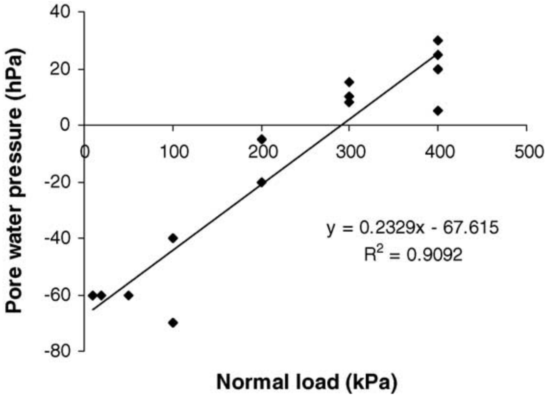

Fig. 4. Average of all pore water pressure values during the shear test as a function of the normal load applied. Data for samples were originally equilibrated at −60 hPa.

Table 4
Static and shear induced changes in effective stress at different normal load and initial pore water pressure

Soil depth (cm)	Initial pore water pressure (hPa)	Effective stress at normal load of Shearing test		Compression test	
		20 kPa	400 kPa	20 kPa	400 kPa
0–15	−60	25.5	396.0	24.7	400.0
40–55	−60	25.4	398.0	24.6	400.0
0–15	−300	33.4	409.8	40.7	422.0
40–55	−300	38.7	406.5	44.8	420.8

in an increased sensitivity of the soil system against any kind of stressing.

4. Conclusions

In a confined compression test, the pre-compression stress value ranged between 42 and 113 kPa for different soil conditions and time settlement, with a critical mechanical load at 300 kPa, where the water pressure had sharply changed. Under dynamic conditions in the shear test, there were positive pore water pressure values for any initial pore water pressure when the normal load exceeded 200 kPa. This mechanical load is called in this paper as critical normal stress.

The evaluations under high initial pore water pressure values (−60 hPa) developed positive neutral stresses during mechanical tests, affecting the results of pre-compression stress and cohesion.

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