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**Plastic and liquid limits in Alpine soils as a function of depth: methods of measurement and relations
with soil properties**

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Abstract

Mountain areas are widely affected by slope failure and instability phenomena, and soil conservation in these regions has become a relevant issue, considering that they are sometimes densely populated. Here the main effects of sudden intense rainfall are conspicuous soil losses not only by erosion processes, but also by soil slips and solifluxion. While steep slopes and scarcely developed soils, with weak aggregates, can increase the potential soil erodibility, determining a consistent transport of aggregates and particles by surface runoff, one of the trigger factors of solifluxion and soil slip phenomena is the presence of scarcely plastic soils, with strength reduction along the profile. Different physical properties can be considered in order to assess soil vulnerability. Soil aggregate stability is commonly measured determining the aggregate loss by wet sieving, and soil plastic properties through the determination of the Atterberg limits. However, only a few efforts have been made to integrate these methodologies.

The objective of this work was twofold: 1) to compare the results of LL determination with the Casagrande device and the cone penetrometer in Alpine soils; 2) to investigate the relationships among soil structural stability, Atterberg limits, fractal dimension and soil chemical properties.

Soil samples were collected in a watershed in the NW Italian Alps from a set of soils, representative of different land unit types, which were classified according Soil Taxonomy and WRB. Samples at different depths were considered for this study, comparing topsoils (0-20 cm, A horizons) and bottomsoils (in the range 40-70 cm, mainly AC and C horizons). For each sample we carried out wet aggregate sieving, and we

calculated the plastic and liquid limits (PL, LL). We also estimated the fragmentation fractal dimension from textural data, in order to describe the particle-size distribution through a single index. For each land unit type, the vegetation cover was surveyed and multivariate statistics were performed in order to study the relations between vegetation and soil strength-stability.

The WAS (wet aggregate stability) analysis evidenced a better structure in topsoils when compared to bottomsoils, despite the sieving time ($p < 0.01$).

Topsoils and bottomsoils also showed a different liquid and plastic behaviour, as bottomsoil were much more vulnerable to liquefaction ($p < 0.01$), indicating that solifluxion phenomena actually represent a natural hazard in the area, as visible from the effects of the flood that occurred in the study area in the year 2000. Multivariate analysis showed some relations between vegetation cover and soil properties affecting aggregation.

Soil stability and plastic behaviour were related to different aggregating agents depending on soil depth. In fact, aggregation and strength were controlled by soil organic matter in topsoils, while in bottomsoils they were mostly influenced by inorganic aggregating agents. This study showed consistent differences between top and bottomsoils, evidencing the presence of diffuse solifluxion and soil slip hazard in the study area, due to a decrease in soil strength and aggregate stability with soil depth. As for surface horizons, organic matter played a fundamental role in soil aggregation, contributing to the conservation of soil structure.

Key-words: Atterberg limits, soil structure, aggregates

Introduction

Soil physical properties related with structure and plasticity are fundamental for soil conservation (Mapfumo and Chanasyk, 1998; Barthes & Rose, 2002; Bronick & Lal., 2005). In fact, soil plasticity can help maintaining aggregate stability (Mbagwu et al., 1991), and a good soil structure can reduce soil erodibility (Le Bissonais, 1996; Six et al., 2000). The conservation of physical properties is particularly important in

Alpine soils (Crosta et al., 2003), where the formation rates are commonly low due to extreme climatic and topographic conditions, and soil losses may occur due to different mechanisms.

Soil losses on Alpine slopes can be due to aggregate break down consequent to abrasion by runoff, as described by Strunk (2003), but also to shallow soil slips-debris flows as reported in Wakatsuki et al. (2005). Crosta et al. (2003), in a study carried out in the Italian central Alps, observed that in poorly plastic soils with low liquid limits (16.3-23.9%) and scarce clay content, soil slips can degenerate in rapidly moving debris flows. In fact, the presence of vertical heterogeneities, i.e. discontinuities in physical properties along the soil profile may result in the detachment of top soils or even subsurface horizons.

Soil structure can be quantified through laboratory measurements such as wet sieving (Kemper and Rosenau, 1986; Zanini et al.,), and the plastic and liquid behaviour are commonly quantified through the Atterberg limits (liquid limit, LL, and plastic limit, PL), following standard procedures (SISS, 1985). LL determination can be achieved with two standard methods. In the Casagrande device, a mass of moist soil placed in a standard cup, then a groove is made with a standard tool in its center. The cup is repeatedly dropped until the groove is closed for 13 mm (½ inch). The moisture content at which it takes 25 drops of the cup to cause the groove to close is defined as the liquid limit. The LL determination with the Casagrande device (or percussion method) is still the most commonly used for road and buildings construction sites. However some problems may arise in case of low soil plasticity (i.e. silty and sandy soils), as reported by Sridharan and Prakash (2000), as the mass of soil may be subject to preferential sliding than flowing towards the groove. The cone penetrometer method a fall cone of angle 30° and weight 80g falls freely into the soil samples at different water contents for a time of 5 s samples. The LL is the water content corresponding to a 20 mm cone penetration. Even if the two methods are considered equivalent for standardised measures, Sridharan and Prakash (2000) observed that they may give slightly different results for some soil types, and they suggested that two different physical mechanisms dominate (i.e. viscous flow in the Casagrande cup, frictional shear resistance in the cone penetrometer test).

The measurements of LL and PL are usually carried out on soils samples from building sites, and to our knowledge measurements on Alpine soils have not been performed.

The assessment of structural and plastic properties in Alpine soils is expected to be particularly important, in order to identify potential vulnerabilities related to soil loss by abrasion and debris flows. However, only a few attempts have been made to integrate the information obtained from traditional structural stability indexes, fractal dimension and Atterberg limits, investigating their relations with soil chemical properties.

The objective of this work was twofold: 1) to compare the results of LL determination with the Casagrande device and the cone penetrometer in Alpine soils; 2) to investigate the relationships among soil structural stability, Atterberg limits, fractal dimension and soil chemical properties.

Materials and methods

The study area is located in the North-Western Italian Alps (Vallée d'Aoste, figure 1), covering a mountain watershed often affected by soil slip and solifluxion events, the latest occurred in 2000. The basin ranges from about 500 to 3200 m ASL, and the climate is moderately dry, with 580 mm precipitation per year. Geology is characterised by alluvial and colluvial deposits with mixed material, and the vegetation cover ranges from grasslands-orchards in the lower portion, to deciduous forest and some extensions of coniferous forests, then pastures and meadows.

Soils are relatively young and the majority of them can be classified as Entisols and Inceptisols according to Soil Taxonomy (Soil Survey Staff, 2006), or Regosols according to WRB (FAO/ISRIC/ISSS, 2006). Samples were collected from 18 soil profiles, representative of the main land units in the study area, at two different depths: 0-20 cm, corresponding to A horizons (surface, S), and about 50-70 cm, generally representing AC and C horizons (deep, D). The choice of the two different depths was done considering that average depth of soil instability phenomena recorded in past events corresponded to the upper portions of soil.

In the soil samples were determined the main physical and chemical properties. pH was determined potentiometrically (SISS, 1985), the organic C and the N content were determined by dry combustion with

elemental analyzer. The CEC (cation exchange capacity) was determined with the BaCl₂-triethanolamine method at pH 8.1 (Rhoades, 1982); the Carbonates content was determined according to the official method in SISS (1985). The Na-dithionite-citrate-bicarbonate extractable Fe (Fe_{DCB}), and NH₄-oxalate extractable Fe (Fe_{ox}) fractions were determined according to the methods proposed by Mehra and Jackson (1960) and Schwertmann (1964), respectively. The soil texture was determined by the pipet method with Na-hexametaphosphate alone and with soil organic matter (SOM) oxidation with H₂O₂. (Gee and Bauder, 1986).

The stability of soil aggregates (1-2 mm fraction) was estimated through wet sieving (at fixed times: (5, 10, 15, 20, 40, 60 minutes), and the % aggregate losses were described following a kinetic approach, through non-linear fitting following the procedure developed by Zanini et al. (1998). The aggregate loss was studied not only in terms of % loss, but also considering the estimated time for the breakdown of 50% of the broken down aggregates according to Zanini et al. (1998).

The liquid limit (LL) was determined both with the Casagrande device and semi automatic cone penetrometer (standard procedure reported by SISS, 1985) and plastic limit (PL) with the thread rolling method described in SISS (1985).

Both chemical analyses and physical determinations were performed three times and then averaged. The statistical treatment of data was performed with SPSS version 12.

Results and Discussion

Soil characteristics

Soil textures are reported in table 1, while the chemical properties are collected in table 2. As visible from table 1, the samples generally showed coarse textures and a limited soil development, as suggested by the low ratio between clay content after SOM removal and after chemical dispersion alone. This is consistent with the incipient development stage of the soils in the study area, which is related also with the limited organic C content, even in topsoils (table 2).

ANOVA showed significant differences between surface and deeper horizons for soil texture in Na-hexametaphosphate (clay, fine and coarse silt, fine sand, always $p < 0.01$, table 1), evidencing some role of SOM as a cement producing aggregation in surface horizons, while no significant difference in classes was observed for texture after SOM removal. Surface soils showed a higher ratio between clay content with/without SOM removal (table 1, $p < 0.05$), indicating a more pronounced presence of clay taking part in aggregation for surface soils. The same was observed for the coarse sand ratio ($p < 0.05$), which was closer to 1 for deeper horizons, characterised by finer aggregation.

Objective 1: comparing the Casagrande device and the cone-penetrometer

LL (both determination methods) was higher in surface horizons (table 3, $p < 0.01$), i.e. the water content required for the transition of topsoils from the plastic to the liquid state was much higher. We observed a discontinuity along the soil profile, as the two soil depths represented two separate populations independent of the determination method used. The same was visible for PL (table 3, $p < 0.01$), i.e. the water content allowing soil to pass from the semi-solid to plastic state. However the plastic index ($PI = LL - PL$) was similar for the two depths (data not shown), ranging from 3 to 12, indicating non plastic or poorly plastic soils, as it can be observed in the field for coarse-textured and poorly developed Alpine soils.

The t test showed that the LL values obtained with the cone penetrometer differed from the ones obtained with the Casagrande device (figure 2). The latter always showed lower LL values, and the difference was almost homogeneous for $LL < 50$, while for higher LL values the difference seemed to be more pronounced.

In any case, the soil classification in terms of PI did not show any shift in the classes we individuated.

Differences between the two methods have been sometimes reported in literature (Sridharan and Prakash, 2000) as influenced by clay mineralogy. Sridharan and Prakash, (2000) observed that the prevalence of a clay mineral in soil may lead to under or overestimation in one of the two determination methods adopted, while in most of the cases a compensating effect is more likely. In the study area most of the soils evolved on mixed morainic, alluvial or colluvial material, so that no clear influence of mineralogical properties could be hypothesised. Moreover, the two LL values in our samples seemed to show a

systematic difference, described by the following relationship: $LL_{CAS} = -0.60 + 0.92 LL_{CP}$ ($r^2 = 0.98$). The lower values of LL_{CAS} might be related to the dominating texture of soils, which were rather homogeneous and poor in fine material, so that the occurrence of sliding instead of flowing movements in the cup could not be completely excluded.

Both methods we used met the requirements of replicability provided by the D4318-00 ASTM standard (ASTM, 1984), but the cone penetrometer method is certainly more rapid, and it seems to be more objective in sample preparation, too, being semi-automatic (Gutierrez, 2006). Considering that the variation in LL values depending on the method used did not imply changes in the classification of soils on the PI basis, the semiautomatic cone penetrometer is therefore recommended.

Objective 2: relations among physical indexes and soil properties

The discontinuity evidenced for the Atterberg limits showed significant relations with aggregating agents, similar for both determination methods. We will therefore present and discuss only the case of cone the penetrometer measurements. For topsoils, the presence of a positive correlation between LL and organic C content ($r = 0.62$, $p < 0.01$) suggested an effect of SOM in increasing LL, i.e. higher amounts of SOM seem to protect soil from liquefaction. The relationship between SOM content and LL is confirmed by the findings of Malkawi et al. (1999), who observed, for illitic soils, an increase of both LL and PL with increasing SOM content, when the SOM is relatively low, which is true in our study area.

The clay ratio was strongly related with PL ($r = 0.76$, $p < 0.01$), but not with the clay contents (table 1) suggesting that the soil liquid limit in the study area is not influenced by the clay content, but rather by the amount of clay taking part in aggregation processes.

In deeper horizons LL was strongly related with the organic C content ($r = 0.76$, $r = 0.79$ for surface and subsurface samples respectively, always $p < 0.01$). However, also some effect of inorganic binding agents was observed, with a positive correlation between both LL and PI with the FeO/FeDCB ratio ($r = 0.64$ and $r = 0.50$, for surface and subsurface samples respectively, always $p < 0.01$).

The difference $LL_{\text{surface}} - LL_{\text{subsurface}}$, quantifying the reduction in liquid limit, was strongly related with the organic C reduction along the profile (figure 3, $r=0.93$, $p<0.01$). A similar relationship was observed for LP and the organic C reduction (figure 4, $r=0.94$, $p<0.01$), while no significant correlation was found between LL and LP reductions and the variation in particle-size distribution. This confirmed the relevant role of SOM in the study area, indicating that not only the amount of SOM is relevant in order to preserve the soil physical properties, but also its incorporation along the profile.

Aggregate stability showed significant discontinuities along the profiles (table 4), too, with a consistent increase in soil vulnerability with depth, as remarked for LL and PL (table 3). The total aggregates loss was lower for surface horizons than for deeper horizons ($p<0.01$), even if wide deviations around the mean were present, probably depending on vegetation cover properties. However, no clear trend with wide vegetation typologies (pasture, grassland, deciduous forest, coniferous forest; data not shown) was observed in the study area. Also the velocity of breakdown differed between the two horizons in terms of the t_{50} parameter (table 4), showing that deeper horizons not only displayed greater aggregates loss, but also showed quicker disgregation.

Soil aggregate loss was related with several properties influencing aggregation. The organic C content was always negatively correlated with the aggregate loss at all sieving times ($r=-0.749$ and -0.629 for the maximum sieving time for surface and subsurface horizons, respectively; p always < 0.01), indicating that SOM played a cementing role independent of soil depth, contributing to the limitation of soil losses. However, subsurface horizons displayed a slight correlation with soil loss at 5, 10, 15, 20 min sieving (r was slightly < -0.50 in all cases, with $p<0.01$) with the ratio Fe_{ox}/Fe_{DCB} . This can be interpreted in terms of soil evolution, as the index represents the amount of poorly crystalline Fe oxides with respect to crystalline (Arduino et al., 1989). In the study area, high indexes corresponded to lower aggregate losses, suggesting that incipient pedogenesis generally results in weaker aggregation.

Conclusion

The objective of this work was twofold: 1) to compare the results of LL determination with the Casagrande device and the cone penetrometer in Alpine soils; 2) to investigate the relationships among soil structural stability, Atterberg limits, fractal dimension and soil chemical properties.

Table 1: soil texture determination in Na-hexametaphosphate and Na-hexametaphosphate plus SOM removal, for different soil depths

Soil property	Surface horizons (S)	Subsurface horizons (D)
Coarse sand (%) Na-hexametaphosphate	40.1 (12.2)	35.3 (14.1)
Fine sand (%) Na-hexametaphosphate	36.9 (10.6)	30.7 (6.1)
Coarse silt (%) Na-hexametaphosphate	8.6 (2.2)	11.3 (3.0)
Fine silt (%) Na-hexametaphosphate	10.9 (4.3)	17.2 (7.0)
Clay (%) Na-hexametaphosphate	3.5 (1.2)	5.4 (3.1)
Coarse sand (%) Na-hexametaphosphate + SOM removal	31.8 (9.9)	31.8 (13.5)
Fine sand (%) Na-hexametaphosphate + SOM removal	29.7 (6.7)	30.3 (6.6)
Coarse silt (%) Na-hexametaphosphate + SOM removal	9.6 (2.5)	11.4 (3.3)
Fine silt (%)	16.8 (2.8)	17.9 (5.8)

Na-hexametaphosphate + SOM removal		
Clay (%) Na-hexametaphosphate + SOM removal	11.0 (4.2)	8.6 (3.6)
Coarse sand Na-hex/Coarse sand H2O2	0.78 (0.20)	0.90 (0.10)
Clay Na-hex/Clay H2O2	3.6 (2.0)	1.95 (0.80)

Table2: soil chemical properties, for different soil depths

Soil properties	Surface horizons (S)	Subsurface horizons (D)
pH	6.8 (1.3)	7.1 (1.3)
CEC (cmol _c kg ⁻¹)	13.0 (5.6)	7.5 (4.1)
BS (%)	75.6 (26.9)	70.7 (37.7)
Org C (g kg ⁻¹)	39.7 (20.1)	10.5 (4.7)
Feox (g kg ⁻¹)	3.0 (1.5)	2.1 (0.1)
FeDCB (g kg ⁻¹)	9.0 (3.0)	8.3 (2.2)

Table 3: Atterberg limits, for different soil depths

Atterberg limits	Surface horizons (S)	Subsurface horizons (D)
LL Casagrande (%)	46 (11)	30 (5)
LL cone-penetrometer (%)	50 (12)	34 (6)
PL (%)	39 (9)	25 (4)

Table 4: soil aggregate stability, for different soil depths

Aggregate losses (%)	Surface horizons (S)	Subsurface horizons (D)
5 min sieving	19.2 (14.1)	46.6 (23.4)
10 min sieving	23.8 (16.7)	57.2 (25.4)
15 min sieving	28.9 (19.8)	61.6 (23.9)
20 min sieving	32.9 (20.2)	65.8 (23.9)
40 min sieving	40.2 (24.6)	70.8 (23.9)
60 min sieving	42.1 (42.1)	75.6 (21.2)
t_{50} (min) *	9.65 (4.8)	5.45 (2.1)

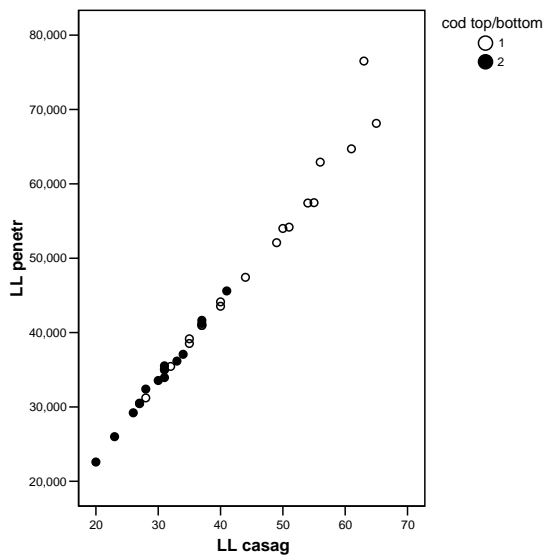
* t_{50} is the estimated time of 50% aggregates breakdown (min)

Figure captions

Figure 1: the study area

Figure 2: LL obtained with the Casagrande device and the cone penetrometer

Figure 3: relationship between LL and organic C reductions along the soil profile



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