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Stress strain behavior of a desaturated loessian lightly cemented soil under triaxial compression test

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Abstract. The upper most modern loess deposits of the central area of Argentina are characterized by an open structure made of fine sand and volcanic silt particles weakly bonded and usually in unsaturated conditions. Heterogeneity in loess is usually present and arises mainly from the non-homogeneous cementation of the soil mass. As saturation increases, the structure of loess collapses even under geostatic pressures. In this work, some results of triaxial compression test performed in loess are presented. Specimens were tested in saturated condition. Testing results allows analyzing the stress-strain behavior of loess in a wide range of strain levels, taking into consideration the influence of structure and confining pressure. Below the yielding stress (collapse), the soil behaves almost as linear elastic and stiffness is governed by degree of cementation. At higher stresses, the collapse potential of the soil skeleton is governed by a complex interplay between applied external pressure and internal forces due to cementation, and probably others attraction-repulsion forces developed at particles of colloidal size. Cementation causes an increase in stiffness, yielding stress and shear strength.

Keywords. Loess,stress,strain, soil modulus

1. Introduction

Loess deposits cover a wide area of the central region of Argentina. The thickness of the deposits ranges from 20 to 60 meters. The word “loess” is a German term that refers to a windblown deposit of silty soil characterized by an open structure. The origin of Argentinean loess and its main physical properties has been extensively described by Rinaldi et al. [1]. Loess of Argentina is composed mainly of platy shape silt particles (40% and 60 %) and sand (5 % to 20 %) from volcanic origin. The clay fraction (20 % to 35 %) is usually illite and montmorillonite. The combined effect of particle shape, origin and particle gradation, render poorly accommodated and open fabric. Usually loess presents some degree of cementation given by clay bridges, soluble salts, silica amorphous, calcium carbonate, gypsum and iron oxide. The high spatial variability of soil properties is originated from a non-homogeneus distribution of cementation during the different postdepositional processes. Then, cementation in

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loess may be found distributed at particle contacts or localized forming nodules and particles aggregates. Additionally, when large amounts of cement (usually carbonates or iron oxide) precipitated at some soil levels, may create a very stiff structure that behaves as a true sedimentary rock-like material which is locally known as "tosca".

Cemented soils can exhibit properties that are very distinctive from those of the original uncemented soil or the freshly remolded one. There is an increasing body of evidence that shows that cementation can have an important effect on the mechanical parameters of the soil. Small strain stiffness increases with the amount of cementing agent respect to the uncemented soil [2][3][4]. Airey and Fahey [5] showed also that cemented soils display very small threshold strain and experience small volumetric strains until decementation begins. Thereafter, at large strains they are prone to exhibit dilative behavior making the effect of initial density less significant on volume changes of the soil. While cemented sands can also liquefy, they exhibit a lower rate of pore pressure generation and an increased resistance to cyclic liquefaction [5][6][7]. Shear strength of soil increases with the amount of cement [8]. The increment of shear strength becomes more significant at low confining pressures [9][10] and is due mainly to an increase in cohesion while the increment in the value of the friction angle still remain controversial [11][12][13]. The load-deformation behavior of cemented soils ranges from brittle at low confinement to ductile at high confinement. The strong dilative tendency, brittleness and post-peak strain softening behavior of cemented soils at low confinement is associated to progressive failure and strain localization [14][15][16]. At the microscale, loading under stress-controlled boundary conditions allows the oriented propagation of contact decementation and the formation of shear bands [17]. In agreement with trends for dilatancy, the severity of strain localization increases with the degree of cementation and with decreasing confinement. While uncemented contractive specimens do not localize under deviatoric drained loading, the same specimen may exhibit strong localization after diagenetic cementation.

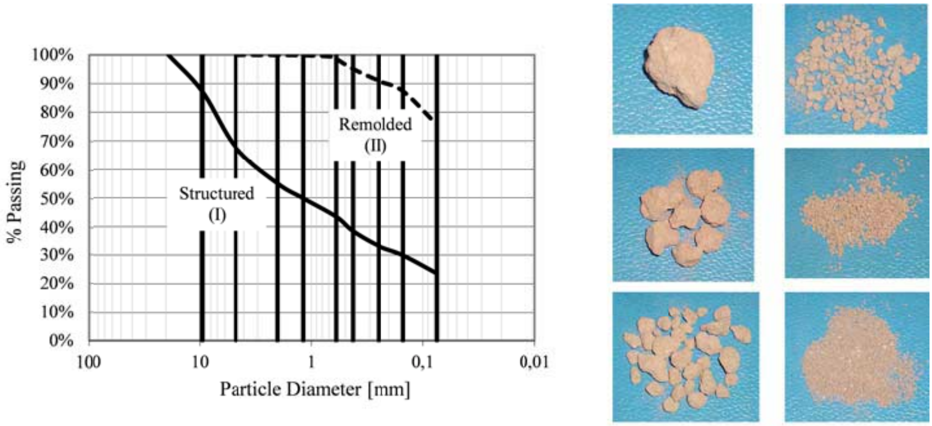
This work presents some fundamental experimental results which highlight the effect of confining pressure and soil structure on the stress-strain behavior of argentinean loess characterized by an open and slightly cemented fabric. Undisturbed and remolded specimens of loess were tested in the triaxial cell in drained conditions. Local displacement transducers were used to measure vertical and horizontal strains.

2. Soil Description and Testing Procedures

Block samples of loess were obtained at the campus of the National University of Córdoba from a 10 meters deep open trench. The evaluation of sampling disturbance by the method used here has been discussed extensively in the work of Rinaldi and Capdevila [18]. Table 1 shows the most significant physical parameters of the soil tested. Figure 1.a displays the grain size distribution curves of a soil specimen obtained from a sample recovered at the site following two different test procedures. Curve (I) was performed by fully remoulding the soil and then following the conventional sieving test [19] and curve (II) was determined by placing the saturated and structured sample on the coarsest sieve of the series and gently washed until the water extracted from last sieve Nº 200 (0.075 mm) become clear indicating the absence of fine particles detached from the aggregates retained in the upper sieves. No energy (eg. vibration or shaking) was applied to the soil as sieving was performed. Figure 1.b shows some pictures of the loess aggregates retained in different sieves. The differences observed between both curves is considered here as a good indicator to evaluate the structuration of the soil. Furthermore, results indicate that cemented nodules remain stable after saturation.

Table 1. Main physical parameters of the soil tested in this work.

Dry Density [kN/m^3]	Natural water content [%]	Liquid Limit [%]	Plastic Limit [%]	Plasticity Index [%]	Passing Sieve #200 [%]	USCS
12.7	17.7	24.5	21.1	3.4	82.5	ML



(a) (b)

Figure 1. a) Sieve analysis performed on structured and fully remolded loess specimens. b) cemented aggregates obtained from sieving analysis of a loess sample without destructuration of the soil.

The triaxial compression tests were performed in the automatic cell ELE Digital Tritest. Vertical strains were measured externally by mean of a Linear Variable Differential Transformer (LVDT), and locally, using a Local Deformation Transducer (LDT). Each LDT sensor consisted of a thin, flexible, strip of phosphor bronze with a strain gage glued at the central section of the specimen under test, similar to those originally proposed by Goto et al. [20]. Two LDTs were placed around the sample to measure vertical strains and a third sensor was placed to measure horizontal strains. LDTs hinges were glued to the sample membrane. Testing specimens of 50 mm in diameter and 110 mm in height were trimmed from the block samples. Table 2 displays the initial testing conditions of the undisturbed specimens prepared here. Undisturbed specimens (U) were saturated in the triaxial cell under the initial confining pressure and with very low gradients (less than 1). Remoulded (D) specimens were prepared from a fully destructured soil by compaction in a mould in 5 successive layers to the desired void ratio. Table 2 also shows the initial testing conditions of the compacted loess specimens. The confining pressure used here were 10 kPa, 20 kPa, 40kPa and 80 kPa and it was applied by mean of air to avoid the damage of electronic components. The Skempton coefficient B was determined from 0.95 and 0.98. The deviatoric load was applied at a velocity of 0.02 mm/min which was calculated to obtain a drained condition.

Table 2: Initial testing conditions of undisturbed specimens of loess tested in triaxial compression. U: Undisturbed. D: Remoulded and compacted

Name	Dry Density [kN/m^3]	Test Moisture Content [%]	Test Matrix Suction [kPa]	Confining Pressure [kPa]
U	12,2	44,2	0	10
	12,3	43,6		20
	12,6	41,6		40
	12,5	42,3		80
D	12,2	44,5	0	10
	12,3	43,8		20
	12,6	41,9		40
	12,5	42,5		80

3. Test Results

3.1. Stress-Strain

Figure 2 displays the triaxial test results obtained for the saturated undisturbed specimens tested at confining pressures of 10 kPa, 20 kPa, 40 kPa and 80 kPa. Curves show strain hardening and ductile behaviour at most confining pressures. The higher the confining pressure, the higher is the increment in the rate of hardening. Here specimens bulge and no stress localization could be observed up to the 6% strain level. In general, higher deviatoric stress curves are obtained with increasing confining pressure. The effect of cementation may be dominant as is observed in Figure 2 where the specimen tested at 10 kPa of confining pressure develops higher values of deviatoric load than that obtained for the specimen tested at 20 kPa. Spatial variability of cement distribution may be responsible for the anomalous behaviour described. It is believed here that the above mentioned specimens tested at 10 kPa are comparatively more cemented than the others. As strain level increases the effect becomes less noticeably.

The influence of soil structure is more pronounced at low strain levels on the secant modulus displayed on Figure 3 which were obtained from the stress-strain curves of Figure 2. Notice that soil stiffness is clearly not related to confining pressure. Opposite as could be expected, some specimens tested at the lower confining pressures display higher modulus. Additionally, modulus degradation does not vary smoothly as a function of strains but jumping. The irregular degradation is observed up to a vertical strain of 0,1% approximately is attributed here to the effect of cementation as elastic energy accumulates at cemented contacts and suddenly is released as stresses overcome shear strength of the binder. At small strains, stiffness is controlled initially by the cemented bonds. At higher strain levels than that corresponding to the elastic threshold, the secant modulus increase with confining pressure and cementation has not significant influence. Thus, soil structure becomes progressively decemented and finally, at very large strains, the influence of confining pressure becomes dominant.

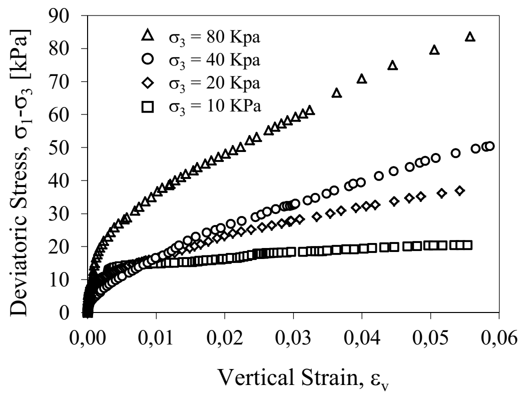


Figure 2. Stress-strain curves of undisturbed specimens tested at different confining pressures and saturated. w = 42.9%

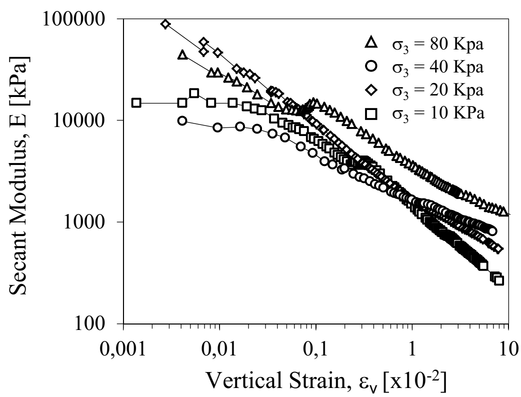


Figure 3. Modulus degradation curves of undisturbed specimens tested at different confining pressures and saturated. w = 42.9%

Figure 4 compares the stress-strain curves obtained for undisturbed and remoulded specimens at two different confining pressures and saturated. No remarkable difference is observed among curves obtained for remoulded and undisturbed specimens tested at similar water content, confining pressures and density. Curves for undisturbed specimens seem to be stiffer at medium strains and more brittle with a clear locus of yielding pressure. Remolded specimens develop a more ductile behavior and the yielding locus is not clearly identified. Figure 5 compares the secant Young modulus for the same specimens of Figure 4. Here, the modulus degradation curves of remolded specimens decay smoothly as would be expected for most unstructured soils. In general, secant moduli of undisturbed specimens are higher than that of the corresponding remoulded specimens at strain levels higher than 0.1%. The authors believe here, that at small strain levels, strains distribute not uniformly throughout the specimen and may be larger or lower in the central portion of the sample registered by the LDT depending on the distribution of cement in the soil mass. Other explanation may be the effect of confining pressure that cause a densification of the remolded specimens, and has no the same influence on the structured specimens. Additional tests are required here to find a more definitive explanation.

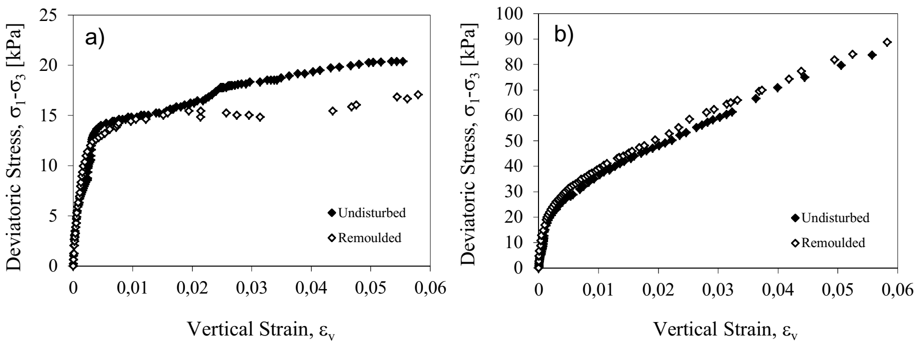


Figure 4. Stress-strain curves of undisturbed and remoulded specimens tested with different confining pressures and saturated. a) σ_3 = 10 KPa and saturated. b) σ_3 = 80 KPa and saturated.

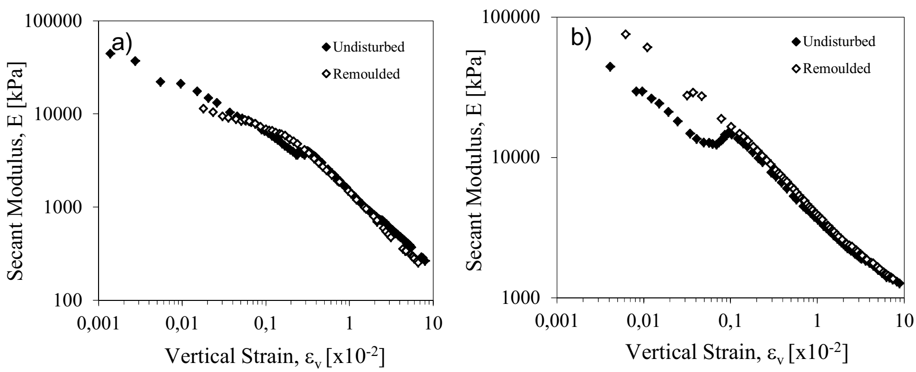


Figure 5. Modulus degradation curves of undisturbed and remoulded specimens tested with different confining pressures and saturated. a) σ_3 = 10 KPa and saturated. b) σ_3 = 80 KPa and saturated.

3.2. Shear Strength

Figure 6 compares the failure envelops corresponding to the CD triaxial test for the undisturbed and the remolded specimens tested in the saturate condition and at similar dry unit weight. The Mohr circles plotted here correspond to a deviatoric stress determined at the 6 % strain level and to the yielding point, determined in the point of maximum curvature. Figure 6 shows that shear strength values of the undisturbed specimen are slightly higher than that of the remolded specimens. The difference between both envelopes reduces as the confining pressure increases. Thus, it is believed here that in saturated conditions, soil structure is broken as confining pressure increases and the behavior of the structured soil previous shearing tends to be that of the remolded. The envelop corresponding to the undisturbed specimen shows a small but true cohesion intercept at zero confining pressure. The friction angle corresponding to the remolded soil is slightly higher than that of the undisturbed soil. The same Figure 6 compares the failure envelops corresponding to the shear strength determined at 6 %

strain level and at that corresponding to the point of yielding for the saturated samples. The results show that the difference between both envelops increases with confining pressure. The yielding envelop corresponding to the yielding stress seems to be less influenced by confining pressure. Both envelopes develop cohesion intercept. Thus, it seems that yielding stress, in saturated condition shear strength, is more affected by cementation and less influenced by confining pressure. After yielding, confining pressure increases shear strength significantly.

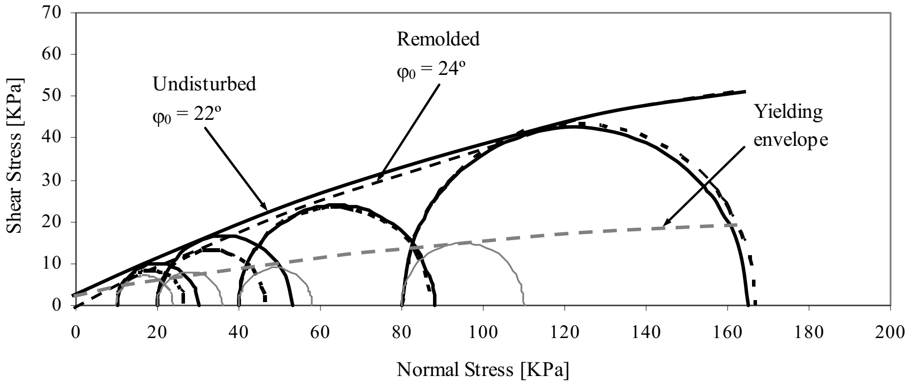


Figure 6. Mohr-Coulomb failure and yielding envelopes corresponding to the undisturbed and remolded specimens tested in drained (CD) and saturated conditions. Shear strength corresponds to the 6 % strain level.

4. Conclusions

A battery of tests was performed in this work to evaluate the influence of soils structure on the stress-strain behaviour of loess soil. The following conclusions can be drawn from this study:

- Cementation of loess has significant effect on the secant modulus at small strain levels (less than 1%). The influence of cementation tends to vanish at higher strain levels. The degradation curve of secant modulus is distinctly jumpy as compared with uncemented soils.
- In general, secant modulus and shear strength of loess increase with increasing confining pressure. However, non-homogeneous spatial distribution aggregates could modify this tendency since the structure of the trimmed specimens could be markedly different due to spatial variability of cementation.
- In saturated loess, the failure envelope of undisturbed specimen presents a small value of true cohesion, that shows the effect of cementation on shear strength but it is reduced significantly with confining pressure.

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