The small-strain shear modulus (Gmax) of Argentinean loess

Le module de cisaillement pour bas deformations (Gmax) du loess d'Argentine

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ABSTRACT: The Argentinean loess has an open structure made of fine sand and volcanic silt particles connected by clay binders. The small-strain shear modulus is an important parameter to characterize the formation, to assess dynamic soil-structure interaction and seismic risk, and to monitor processes taking place within the soil mass. The characteristics of the Argentinean loess are reviewed first. Then, results of an experimental study are presented where the mid-strain compressibility and small-strain shear modulus are measured in a modified odometer cell. The complex interplay between confining pressure and degree of saturation on G_{max} is highlighted. Sampling and remolding effects are discussed.

RÉSUMÉ: Le loess du l'Argentine a une structure ouverte constituée de particules de sable et du limon volcanique reliées par des ponts d'argile. Le module de coupe á basses déformations constitue un paramètre important pour la caractérisation de la formation, l'analyse de l'interaction dynamique entre sol et structure ainsi du risque sismique, et l'observation des différents processus des sols. D'aborts, nous révisons les characteristiques du loess argentine. Alors, nous présentons les résultats d'une étude expérimentale dans laquelle nous avons fait des mésures dans une odométre modifiée de la compressibilité mi la tension et du module de coupe á basses déformations. Nous avons souligner l'interaction complexe entre la pression du confinement et le degré de saturation au G_{max}. Les effets des méthodes pour prendre des échantillons et pour ré-moulurer sont discutés.

1 INTRODUCTION

Loess is one of the most abundant soil formations on the continental surface of the world. The Argentinean deposit is the largest one in the southern hemisphere, with a thickness that varies between 20 and 60 meters (Teruggi, 1957). Loess is a wind-blown formation. It can experience high volume changes when loaded or wetted, thus it is classified as collapsible in the unstable soils group (Aitchinson, 1973).

Research efforts in the past decades have focused on understanding collapse mechanisms, the relationship between collapse and soil structure, the evaluation of collapsibility potential and the modeling of the stress-strain response. Concepts rooted in the field of unsaturated soil mechanics seem to explain correctly the behavior of loess under static load conditions (Alonso and Gens, 1994; Barton, 1994). Recent studies have addressed the dynamic response, with emphasis on large strain effects (eg. Singh and Chew, 1988; Koester, 1994; Ishihara and Harada, 1994 and Finn et al., 1994). The small-strain dynamic shear modulus and damping ratio of loess are less known; available data for the Argentinean loess can be found in Rinaldi and Redolfi (1996), Rinaldi, Santamarina and Redolfi. (1998), Rinaldi and Clariá (1999) and Clariá and Rinaldi (2000) and in Hardcastle and Sharma (1998) for the loess in eastern Washington.

This document presents a reassessment of those results, with emphasis on fundamental mechanisms, to provide new insights into the dynamic behavior of loess and its relationship to soil structure. The microstructure of the loess, its compressibility and collapse mechanisms are briefly reviewed. Then, the effect of the degree of saturation and the mean confining pressure on the small-strain shear modulus of undisturbed specimens of loess is analyzed.

2 SOIL STRUCTURE

The most significant difference between the Argentinean loess and other loess formations around the world is the presence of volcanic glass minerals as the main components of the silt and sand particles (Teruggi, 1957, Moll and Rocca, 1991). Quartz and feldspars are also abundant. The main clay minerals are montmorillonite and illite. Calcium carbonate usually ranges between 5 and 10 % and it is present in the form of nodules or precipitated at particle contacts. When gypsum and iron oxides are present, the soil is very stable even in the presence of water. Loess is alkaline in nature (Ph > 8). The typical range of grain size distributions is: sand (5 % to 15 %), silt (40 % to 60 %), and clay (20 % to 35 %). The plastic index varies from 4 % to 12 % and the natural moisture from 12 % to 18 %. Engineering properties of the Argentinean loess and its differences with other loess deposits are addressed in Rocca (1985).

Figure 1.a shows a scanning electron microscope (SEM) photograph of the fabric of loess around a macropore. A detail of the structure is shown in Figure 1.b. Clay minerals and precipitated salts are observed on the surface of the silt and sand particles. Clay minerals, specially montmorillonite, may have formed after deposition, from the chemical weathering of the volcanic glass and plagioclase minerals. There is no clear evidence of clay bridge structures connecting the largest particles, as observed in other loess deposits (see for example Kie, 1988). Instead, coarser particles seem to accommodate around macropores in a disor-

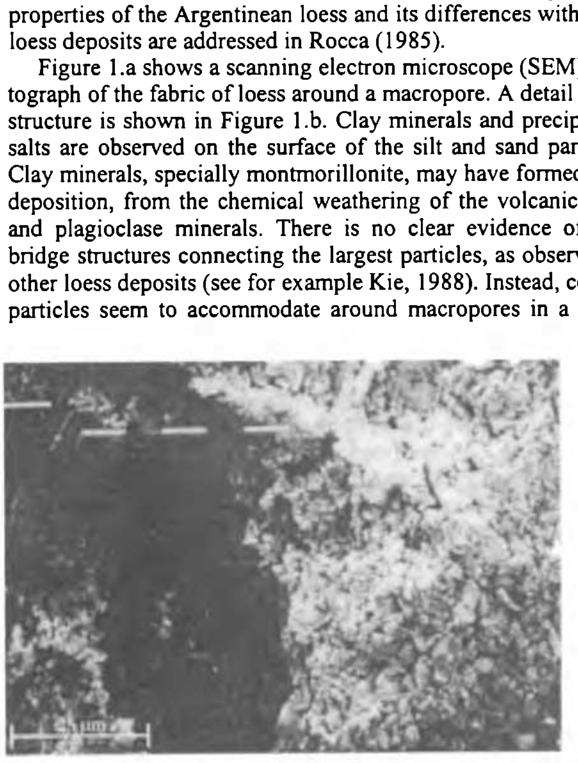

Figure 1.a: SEM photograph (X80) of a macropore in the structure of loess.

Figure 1.b: SEM photograph (X250) of sand and silt particles of loess.

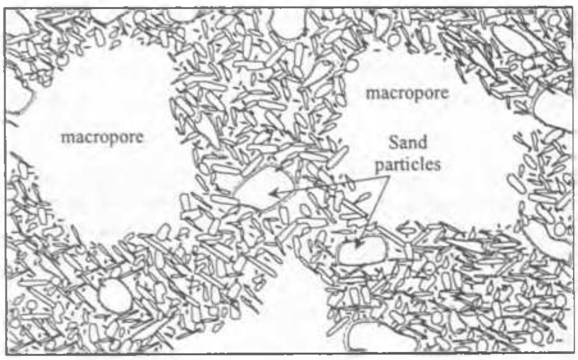

Figure 2: Fabric of the Argentinean loess - Sketch based on SEM images.

dered manner. The presence of clay minerals and other cementing agents is observed at contact points. Figure 2 shows a sketch of the structure interpreted from SEM photographs of Argentinean loess. This structure resembles the model suggested by Gourui (1981).

When water permeates into loess, clay particles and soluble salts hydrate, and the strength of contacts weakens (this occurs before saturation is reached). Then, the applied load may suffice to cause the collapse of the structure around macropores; micropores close at higher stress. (The evolution of interparticle forces during wetting and collapse is analyzed in Rinaldi, Santamarina y Redolfi, 1998. The relative influence of macro and micropores on soil deformation is addressed in Luttenegger and Saber, 1987 and in Amirsoleymani, 1994).

3 COMPRESSIBILITY AND COLLAPSE (*Medium-Strain*)

Loess has all the characteristics of highly compressible soils (Feda, 1994): large initial void ratio, weak interparticle bonding, low initial water content, poor gradation and angular grains. The compressibility of Argentinean loess is studied by subjecting undisturbed specimens with different degrees of saturation to k_o-loading in a odometer cell. Specimens were trimmed from a block sample gathered from a 2 m deep open trench, at the University of Cordoba campus.. The formation has an initial dry unit weight $\gamma_d = 12.6$ kN/m^3 and plasticity index PI = 3.4.

Figure 3 shows the measured load-deformation response. All unsaturated specimens show low deformation until the collapse pressure is reached. The collapse pressure is herein selected at the point of maximum curvature in the semi-log load-deformation response. The saturated specimen does not show a distinct collapse pressure. Results also indicate that the collapse pressure decreases and the compressibility of the soil increases as the degree of saturation increases. Contact-level cementation, suction forces and electrical forces contribute to the strength and the stiffness of the structure at low moisture content. The void ratio of unsaturated specimens remains higher than the void ratio

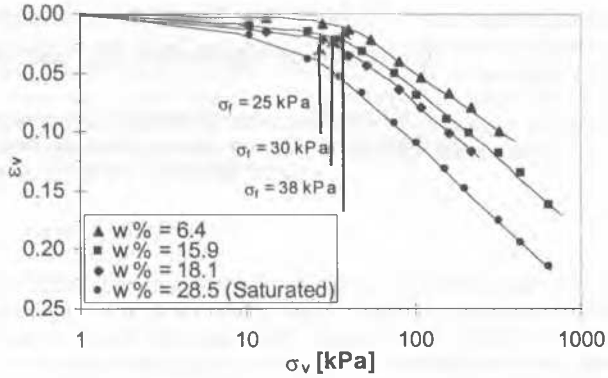

Figure 3: Load-deformation response of undisturbed specimens of loess subjected to k_o loading (modified from Clariá and Rinaldi, 2000).

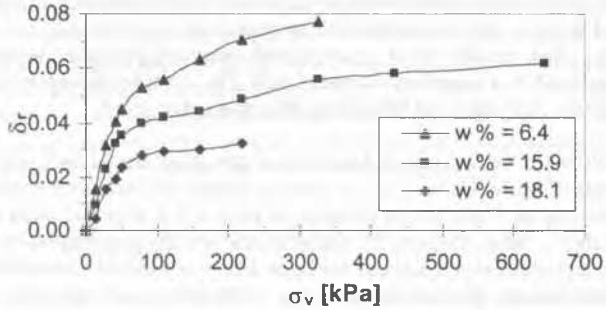

Figure 4: Variation of the coefficient of collapsibility with pressure for the undisturbed and unsaturated specimens (refer to Figure 3).

of the saturated specimen through out the stress range covered in this study.

The coefficient of collapsibility (δ_r) has been defined elsewhere as the ratio of the additional compression due to fully saturation of the soil (Δe) to the initial sample height previous saturation (1+e) at the same state of stresses or conversely, as the difference in strain developed by the soil in saturated (ε_s) and unsaturated (ε_u) state at the same stress level.

$$\delta_r = \frac{\Delta e}{(1+e)} = \varepsilon_s - \varepsilon_u \quad (1)$$

The relationship between the collapsibility and structure has been discussed by Feda (1994) and Feda (2000). Notice that, the larger the value of δ_r the larger the collapse and closure of pores. Figure 4 shows the variation of δ_r with confining pressure for the unsaturated samples of Figure 3. It can be inferred from this result that in front of water, the collapse of the structure show sudden steps (similar to "stick slip" in frictional systems). The larger initial slipping may be due to the closure of the macropores. The pressure of collapse can be considered the starting of the debonding process. Massive collapse starts at the collapse pressure.

4 WAVE VELOCITY AND COLLAPSE (*Small-Strain*)

The shear wave velocity of soils depends on the mean confining pressure (σ_m), the void ratio (e - this macro-scale parameter is related to the micro-scale coordination number), the degree of saturation (S), and the degree of cementation (c) of the soil. Piezoceramic bender elements are mounted on the top and bottom platens of the odometer cell to monitor the evolution of the shear wave velocity (V_s) during loading.

Figure 5 shows the variation of V_s with vertical pressure σ_v obtained for the same unsaturated undisturbed specimens tested in the modified odometer cell. Unsaturated specimens exhibit significant shear wave velocity even at zero confinement, and the value of initial V_s decreases with the degree of saturation, therefore, V_s is suction-cementation controlled at low stress. As load is applied, V_s increases until a peak value is reached near the collapse pressure. At high stress, the velocity-stress re-

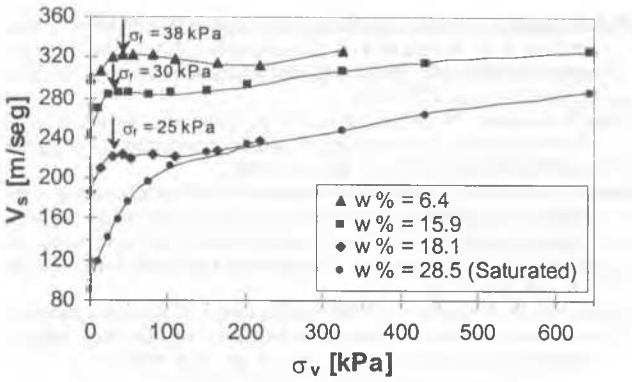

Figure 5: Small-strain response. Variation of shear wave velocity with vertical pressure for undisturbed specimens of unsaturated loess (data from Clariá and Rinaldi, 2000).

sponses for the unsaturated specimens appear to asymptotically approach the velocity stress response for the saturated specimen. This trend suggests that the effect of the applied stress gains relevance over the effect of suction and cementation at high stress. The velocity V_s in the saturated specimen increases continuously with the applied stress, resembling the standard power velocity-stress response in uncemented, dry or saturated granular media.

The observed trend for unsaturated specimens is schematically captured in Figure 6. The stiffness at low confinement is determined by the degree of saturation: the higher the saturation, the lower the contribution of suction to stiffness (Cho and Santamarina, 2001). The stiffening of the specimens at low confinement may reflect the closure of hairline cracks and early local collapse accompanied by the increase in interparticle coordination. Strain energy accumulates up to the collapse load when the shear strength of contact bonds is overcome and the structure undergoes massive collapse. After the peak, the weakening effects of debonding exceed the stiffening effect of the increase in interparticle contacts. After collapse a new structure gradually develops. At high stress, the rate of debonding is low and the structure evolves towards the structure of an initially uncemented specimen. Wave velocity increases monotonically at a gradually decreasing rate.

The global behavior described for loess specimens resembles results reported by Baig et al. (1997) and Fernandez and Santamarina (2000) for cemented specimens: (1) cementation stiffens the structure of soils at small-strains and low stress, (2) stress changes may cause debonding and the reduction in V_s, and (3) stiffness becomes stress-controlled at high stress. These results suggest that unsaturation (in the pendular regime) and cementation have similar effects on small strain stiffness. Therefore, the behavior of loess can be analyzed within the framework of unsaturated soil mechanics or within the conceptualization of cemented soils but with binder strength susceptible to water content.

The maximum shear modulus (G_{max}) can be computed from

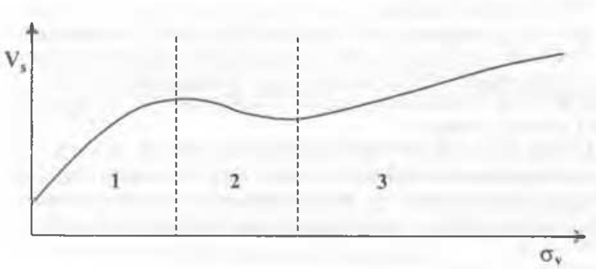

Figure 6: Velocity-stress response of unsaturated, undisturbed loess. 1: Low stress range: hairline cracks close and early local collapse develops; strain energy is stored. 2: Massive collapse of the structure and closure of macropores. 3: Re-structuration. The effect of the state of stress exceeds the effect of suction and any remaining bonding.

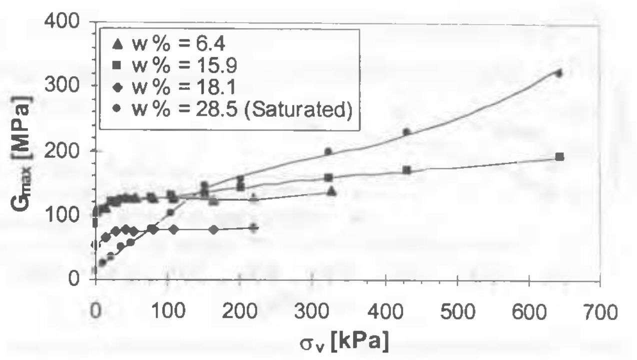

Figure 7: Variation of shear modulus G_{max} with vertical pressure for undisturbed specimens of loess.

the shear wave velocity (V_s) and the soil mass density (ρ):

$$G_{max} = \rho \cdot V_s^2 \qquad (2)$$

Figure 7 shows the variation of G_{max} with the vertical stress (σ_v) for the data plotted in Figure 5. As the mass density changes significantly upon collapse, the drop in shear wave velocity after the collapse load vanishes when the data are interpreted in terms of G_{max}. Furthermore, the saturated specimen exhibits higher values of G_{max} than the unsaturated specimens at high confinement, because the higher compressibility of the saturated specimen renders a denser medium (refer to Figure 3). These observations explain the apparently contradictory results obtained by Hardcastle and Sharma (1998).

Data may be re-interpreted in terms of strains. In particular, there is a threshold strain for de-cementation and/or the failure of small menisci at contacts. As the strain level approaches this threshold strain, the stiffenning effects of cementation and unsaturation are gradually lost.

5 REMOLDING AND SAMPLING EFFECTS

Stiffness loss may occur during sampling and remolding. Sampling effects vary with the degree of cementation, moisture content and in situ state of stress. In the case of menisci, the higher the degree of saturation the higher the strain required for menisci failure, and the less sensitive is the structure of loess to sampling. Disturbed specimens will exhibit lower stiffness in the lab than in situ. A severe case of sampling disturbance is simulated in the laboratory by remolding the sample (manual desegregation) and sieving it through the # 40 sieve. This process effectively destroys the macro-structure of the soil but preserves the meso-scale of aggregations. Figure 8 shows compressibility curves for the remolded and undisturbed specimens at similar dry unit weight and moisture content: (1) overall, both specimens show similar trends, (2) the undisturbed specimen shows a break at the collapse pressure, and (3) the remolded specimen is more compressible at high vertical pressures.

Figure 9 shows the variation of G_{max} with confinement for the undisturbed and the remolded specimens. Values for the undisturbed specimen are higher than for the remolded specimen, and

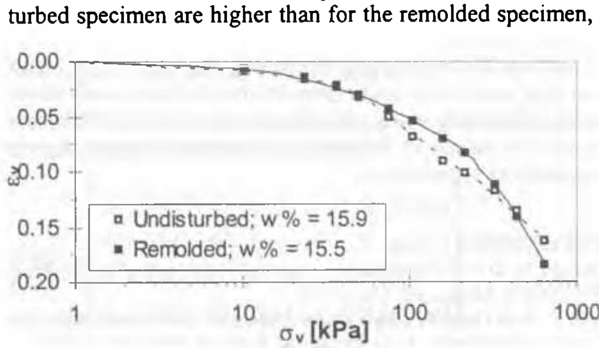

Figure 8: Compressibility curves for remolded and undisturbed loess at similar moisture content and dry unit weight.

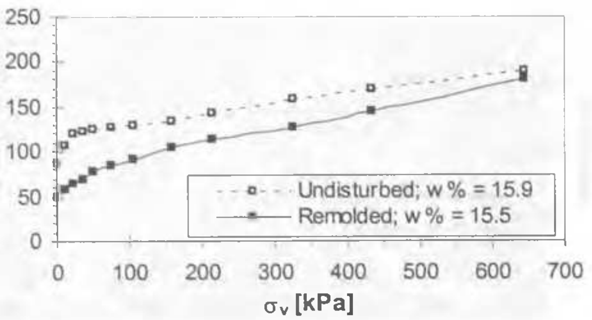

Figure 9: Shear modulus measured for unsaturated remolded and undisturbed specimens of loess. Specimens have similar moisture content and dry unit weight.

show a peak near the collapse pressure. At high confinement, the stiffness of the two specimens becomes stress-controlled and tend to a similar value. At low confinement, the stiffness of the undisturbed specimen is twice higher than the stiffness of the remolded specimen. This drop in stiffness is indicative of the potential impact of sampling disturbance. (Note that the specimen denoted as "undisturbed" may have suffered some disturbance itself. Therefore, the ratio between shear stiffness in situ and in the lab can actually exceed the value of 2 measured with these specimens). While menisci may also develop between aggregations in the remolded specimen, the rate of menisci development is slow at low moisture content (vapor pressure controlled); this is a form of thixotropic recovery. Note that these specimens have different meso-structure, in particular, significant differences in the pore size distribution of macropores is expected..

6 CONCLUSIONS

The middle and small-strain properties of loess reflect its unique internal structure. The main observations from this study follow:

a. The structure of Argentinean loess resembles a dual-porosity medium where macropores are formed by a matrix of clay minerals and salts surrounding sand and silt grains.

b. The high compressibility of loess reflects its high initial void ratio, weak interparticle bonding, low initial water content, poor gradation and grains with elevated angularities.

c. The structural stability of the granular matrix depends on contact-level cementation and suction forces between particles.

d. Collapse can be triggered by increasing the applied load or the moisture content (collapse takes place before saturation is reached). At constant moisture content, massive collapse takes place near the collapse pressure. The collapse pressure is not constant for a given loess formation, but it decreases with increasing moisture content.

e. The variation in shear wave velocity with stress exhibits a peak near the collapse pressure. At low stress, stiffness is related to moisture content (suction) and diagenetic effects such as cementation. At high stress, stiffness is determined by the state of stress.

f. Stiffness-stress trends differ significantly from velocity-stress trends, due to the important changes in mass density that accompany collapse.

g. Sampling disturbance and remolding may render specimens with similar mid-strain compressibility but different small-strain modulus. Therefore wave velocity measurements complement odometer test results in enhancing the characterization of loess for engineering applications

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