From Fundamentals to Applications in Geotechnics
D. Manzanal and A.O. Sfriso (Eds.)
IOS Press, 2015

doi:10.3233/978-1-61499-603-3-2031

Behavior of collapsible loess saturated with NAPL in confined compresion tests

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Abstract. Loess from the central area of Argentina are unstable soils with mechanical properties highly dependent on moisture content. These soils have a macro skeleton that collapses when either loads increase and/or water enter into the soil pores. This collapse mechanism affects deformation modulus and strain-stress behavior of this soil. This research analyzes experimental results obtained in triple-oedometer tests performed in silty loess. Three identical samples of different silty loess families were tested in confined compression tests at natural moisture content, fully saturated with water and fully saturated with a Non-Aqueous Phase Liquid (NAPL). The obtained results allow determining the relative importance of suction, salt dissolution, and particle-fluid interaction mechanisms on the mechanical behavior of the collapsible loessical silts from the center of Argentina.

Keywords. Loess, soil contamination, collapse, unsaturated soil, oedometer

1. Introduction

Argentinean loess has mechanical properties highly dependent on moisture content and its behavior has been extensively studied during more than 40 years [1-2]. This type of aeolian soils are composed by sand and silt particles jointed by clay bridges and precipitated salts that form macropores, which undergo high volume decrease when loaded or wetted.

However, the mechanism responsible for the soil collapse observed at macro-scale, and whether the dissolution of precipitated salts or the expansion of clay bridges between coarser particles can be responsible for that emergent behavior is still uncertain.

At the same time, there are several cases where this soil suffered contamination with organic liquids, many times related to accidental spills during oil transport and leakage in pipes and oil tanks in gas stations. There are significant evidences that the addition of organic liquids to soils affects physical and mechanical properties [3-6]. However, in the case of Argentinean loess most of studies involving the presence of NAPL in soil pores focus on the effect of contamination on dielectric permittivity and hydraulic conductivity but there is no evidence of how NAPL affects loess mechanical properties.

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Then, the purpose of this work is to evaluate the stress-strain behavior of loess from the center of Argentina under zero lateral displacement. The effect of pore fluid type and amount is evaluated by testing specimens at natural moisture content, saturated with water and saturated with a non-miscible organic liquid.

2. Behavior of the Loess under Study

The loess under study has mechanical properties highly dependent on moisture content and aging. The main significant mechanical properties of this soil have been extensively reported in the last decades [7-10]. These quaternary sediments are known as Fm. Pampeana, and have variable thickness from 100 to 600 meters. The soil is classified as primary or secondary loess depending on whether or not additional transport agents were present in the past. Clay, silt and fine sand particles were deposited by wind (primary loess) and water, snow or gravity may disturb and transport particles forming secondary loess deposits [11]. Different diagenetic processes such as hydration, dissolution of soluble salts, gypsum formation are also responsible for the transformation of primary loess to secondary loess [12].

The coarser particles form a rigid skeleton that is responsible for the loads transfer, either body or external loads. A small percentage of particles share and transfer most of the load. The clay fraction separates forming joints or bridges between the sand and silt particles and soluble salts precipitate in the contacts. These sediments develop significant collapse due to water or effective pressure increases. This collapse is frequently associated to the dissolution of the precipitated salt, to the rupture of clay bridges due to the expansion of clay minerals when water content increases or to the instability of the chain of particles under a given moisture content and applied stress. Table 1 summarizes relevant properties of the loess under study.

Table 1. Main properties of Argentinean Loess compiled from literature [13-14].

Property	Unit	Value			
		Min.	Mean	Max.	COV
Dry unit weight	kN/m^3	11.2	13.2	14.5	0.05
Moisture content	%	4.5	15	39.0	0.32
Liquid limit (LL)	%	17	24.4	39	0.11
Plastic index (PI)	%	0	3.5	8.0	0.42
Sand fraction (> 0.074 mm)	%	1	5	15	N/A
Silt fraction (0.074 mm – 0.002 mm)	%	40	80	91	N/A
Clay fraction (< 0.002 mm)	%	2	5	25	N/A
Yielding pressure	kPa	10	53	540	0.58
Undrained friction angle, ϕ_u	o	0	11.1	24.0	0.49
Undrained cohesion, c_u	kPa	0	17	135	1.30
Drained friction angle, ϕ'	o	26	28	30	N/A
Drained cohesion, c'	kPa	0	6	8	N/A
Confined modulus (natural moisture and at σ_v=100 kPa)	kPa	1500	4000	8000 (*)	N/A
Confined modulus (saturated and at σ_v=100 kPa)	kPa	1000	1900	4000 (*)	N/A

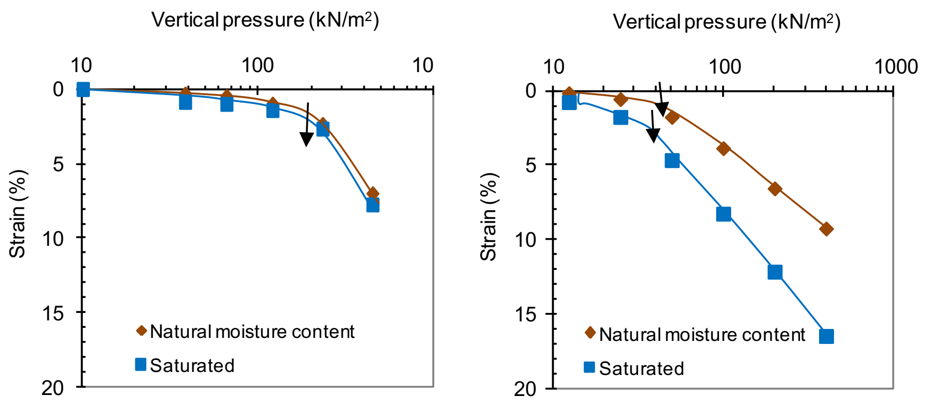
Note: * = higher values can be observed in cemented samples

Only cemented samples that arise when the soil particles suffer cementation due to calcium carbonate or silicates precipitation don't develop collapse and behave as a weak rock.

Figure 1 presents experimental results from selected double-oedometer tests performed in samples of cemented and collapsible loess. Two very different mechanical responses were identified [12].

Compressibility curves of the cemented samples tested at natural moisture content and flooded with water show the same trends with almost the same strain levels at each effective vertical pressure (Figure 1a). This behavior is typically observed in the case of cemented loess regardless of the dry unit weigh or the initial void ratio of the soil. Therefore, mechanical behavior is mainly controlled by the cementation agent (type and amount) and confinement. This loess sample is non-collapsible and thus, yielding pressure obtained for the unsaturated specimen results almost coincident with the preconsolidation pressure of the saturated sample.

Figure 1b shows typical double-oedometer tests performed in collapsible loess. The specimen tested under unsaturated condition show smaller vertical strains than the one that is flooded with water. In addition, preconsolidation pressure obtained in the saturated specimens results significantly lower than the yielding pressure of the unsaturated sample [15]. The comparison of yielding and preconsolidation pressure with the in-situ effective vertical pressure are used to differentiate between loess that may collapse due to the actual overburden pressure (cannot support the self weight when flooded) from those that significantly settle but can support their self weight when flooded.



(a) (b)

Figure 1. Typical double oedometer test results for Argentinean Loess: a) cemented specimen, b) collapsible specimen (Results reported by Francisca [16]).

Collapsibility is also related to the natural moisture content of loess. Specimens with lower natural moisture content show higher collapse after saturation. Different authors states collapse can be related to that salts dissolve and clays tend to expand when loess is wetted, collapsing the soil macro-structure [17-18]. Details of different classification systems for collapsible soils can be found in specialized literature [19].

3. Materials and Methods

Undisturbed samples were obtained from 6 geotechnical investigations performed in the Province of Cordoba, Argentina. The collection procedure consisted in man-made excavations until the sampling depth was reached where undisturbed specimens with 25 cm in diameter and 35 cm in height were then extracted, preserved in double plastic bags and shipped to the laboratory at the Universidad Nacional de Córdoba. Once in the lab, the specimens were stored in a wet chamber until testing.

Triple-oedometer tests were carried out by means of running confined compression tests under zero lateral deformation. Three specimens were tested for each soil sample and testing point, and therefore, the overburden pressure, initial void ratio and natural moisture content were identical. First sample was tested at natural moisture content, the second one was flooded with water and the last one was flooded with kerosene.

Consolidation and compressibility curves were obtained for each test. From the compressibility tests a water relative collapse (δ_{w_col}) and oil relative collapse (δ_{o_col}) were obtained as follows:

$$\delta_{w\_col} = \varepsilon_{nat} - \varepsilon_{w\_sat} \tag{1}$$

$$\delta_{o\_col} = \varepsilon_{nat} - \varepsilon_{o\_sat} \tag{2}$$

Where ε_{nat}= strain level at natural moisture content, ε_{w_sat}= strain level when saturated with water, ε_{o_sat}= strain level when saturated with oil. Strain levels in equation (1) and (2) are stress dependent and therefore relative collapse is also stress dependent.

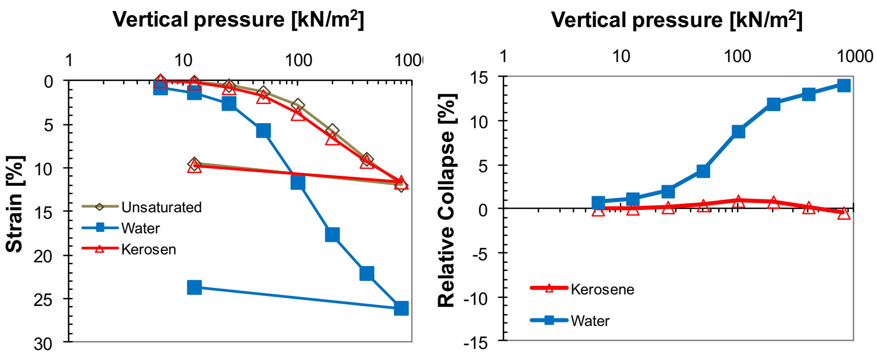
4. Results and Discussions

4.1. Triple-Oedometer Tests

Figure 2 presents a triple-oedometer test performed in collapsible loess. Obtained result shows that compressibility curve of the specimen tested at natural moisture content significantly differs from that of the specimen flooded with water. The specimen flooded with water suffered higher deformations than the one tested under unsaturated state, as expected for collapsible soils. Similar trends were obtained for all collapsible samples.

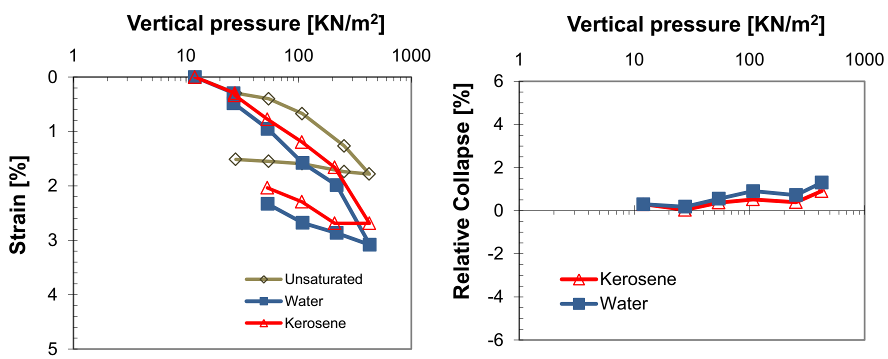
A different behavior was obtained in cemented specimens (Figure 3). Very similar compressibility curves were obtained for the three specimens meaning that the pore fluid has little influence on the stress-strain behavior of cemented loess. According to the experience of the authors, this behavior does not depend on the initial void ratio (or dry unit weight). Indeed, some cemented primary loess were identified having extremely low dry unit weight (close to minimum value reported in Table 1) but with very high stiffness and preconsolidation pressure (higher than the values reported in Table 1). Similar trends were obtained for all cemented samples.

These experiments can be considered as an extension of the well-known double-oedometer tests used to evaluate the relative collapse of soils. Behavior of soil under natural moisture content and flooded with water provides the collapsibility of soil while flooding the soil with kerosene gives information about the mechanisms responsible for the observed collapse. Note that even specimens flooded with water and kerosene are both saturated, capillary effect are expected for the specimen flooded with kerosene due to the presence of meniscus and the water-kerosene interfacial tension. However, given that surface tension of water is significantly higher than surface tension of all organic liquids, capillarity has little effect on the mechanical behavior of kerosene saturated loess.



(a) (b)

Figure 2. Triple-oedometer test in collapsible loess with initial moisture content w=13.6% and initial dry unit weight γd=12.2 kN/m^3: a) compressibility, b) relative collapse



(a) (b)

Figure 3. Triple-oedometer test in cemented loess with initial moisture content w=16% and initial dry unit weight γ_d=13.0 kN/m^3: a) compressibility, b) relative collapse

Figure 4 shows relative collapse curves for collapsible loess samples obtained in the geotechnical site investigations. Figure 4a shows computed water relative collapse (δ_{w_col}) while Figure 4b shows the corresponding oil relative collapse (δ_{o_col}) curves obtained from triple-oedometer tests. Dry unit weights ranged from 12.2 kN/m^3 to 13.9 kN/m^3 while natural moisture contents were between 4.1% and 13.7%.

Different relative collapse limits were established to differentiate collapsible from non-collapsible soils [19-21]. This work assumes that initial collapse pressure is that capable of produce a relative the collapse higher than 0.015 (1.5%), in coincidence with the Chinese criteria [21]. Therefore, results shown in Figure 4a indicate that all samples can be considered as collapsible and the initial collapse pressures were lower than 22 kN/m^2. However, the same loess samples develop initial collapse pressure higher than 200 kN/m^2 when flooded with kerosene (Figure 4b).

Obtained results in all tested cases show that collapsibility of loess depends on the stress level, presence of nodules and soil structure. The higher the amount of nodules, the lower the expected relative collapse and the higher the constrained soil modulus [16].

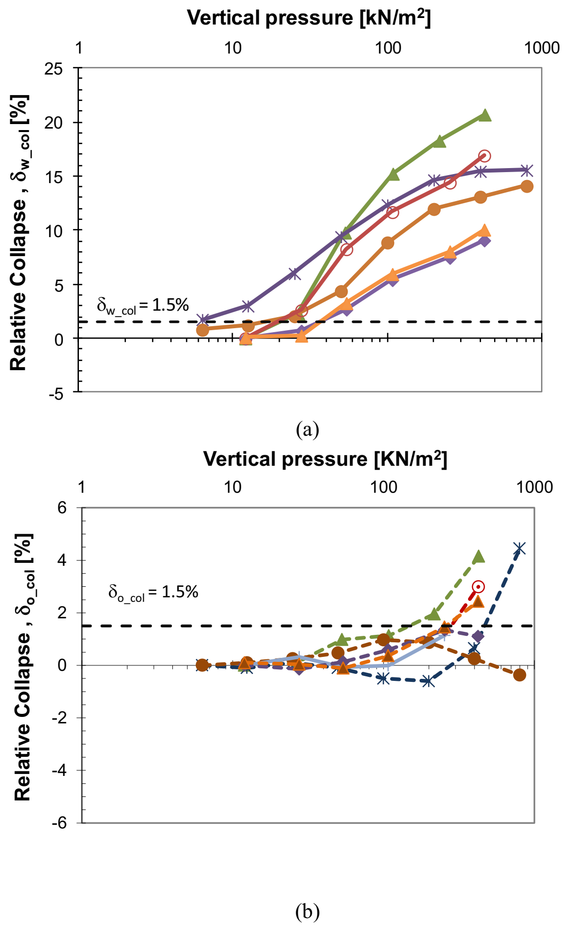


Figure 4. Relative collapse of loess samples: a) water saturated, b) kerosene saturated

Trends observed in Figure 4b indicates that collapsible loess does not suffer collapse when saturated with a non-miscible organic liquid. Only at effective vertical pressure higher than the saturated preconsolidation pressure which is lower than 30 kN/m^2 for all samples, the oil relative collapse develops a slightly increase. In addition, δ_{o_col} results higher than 1.5% when the vertical pressure surpasses the unsaturated yielding pressure. This phenomenon produces a decrement of the soil elastic modulus that may be significant only at high pressures for all practical purposes.

Obtained results confirm that uncemented primary loess behaves as an unstable soil showing collapse due to the increase in water content, but behaves as non-collapsible when saturates with non-miscible organic liquids. Therefore, soil collapse observed at macro scale cannot be associated to the decrease of soil suction. Dissolution of precipitated salt and expansion of clay particles forming bridges between coarser silt and sand particles are responsible for the soil collapse. This behavior arises when loess is saturated with water but is hidden when saturated with a non-aqueous phase liquids, given that this fluid cannot dissolve precipitated salts and clays behave as non-plastic and show no swelling potential in presence of organic liquids [22].

5. Conclusions

This work proposes the use of triple-oedometer tests to evaluate the behavior of collapsible loess. The main conclusions can be summarized as follows:

- Loess from the central part of Argentine develops significant collapse when water content or pressure increases. Hence, vertical deformations increases and bridges of particles that form the rigid skeleton that transport loads break when loess is saturated with water.
- The increase of water content weakens the strength of particle contacts and modifies the macro-scale behavior of loess. However, cemented loess doesn't develop collapse when saturated. Samples with cementing nodules may develop a small collapse.
- Mechanical behavior of loess is significantly affected by the presence of non-miscible aqueous phase liquids (e.g. oil). All tested loess behaves as non-collapsible soils when is saturated with oil. When the applied effective vertical pressure surpasses the saturated preconsolidation pressure, the relative collapse starts to increase slightly.
- Relative collapse depends on stress level, presence of cementation or cemented nodules and type of liquid inside soil pores. The initial collapse pressure of non-cemented loess saturated with water is significantly lower than the initial collapse pressure of the same soil saturated with kerosene. This difference arises because kerosene cannot dissolve precipitated salts or expand clay particles that form bridges between coarser particles.

Acknowledgments

This research was partially financed by SECyT-UNC, Facultad de Ciencias Exactas Físicas y Naturales, Universidad Nacional de Córdoba (FCEFyN-UNC), Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), FONCyT (PICT-2014-3101) and Secretaría de Ciencia y Tecnología – Ministerio de Industria, Comercio, Minería y Desarrollo Científico y Tecnológico Provincia de Córdoba.

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