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Volume change behavior of Argentinean collapsible loess inundated by organic liquids

Comportement au changement de volume du loess pliable argentin inondé de liquides organiques.

Franco M. Francisca, Ignacio Giomi & Marcos A. Montoro
Universidad Nacional de Córdoba, Facultad de Ciencias Exactas, Físicas y Naturales, X5016 CGA, Córdoba, Argentina.
Instituto de Estudios Avanzados en Ingeniería y Tecnología (IDIT), CONICET and Universidad Nacional de Córdoba, X5016 CGA, Córdoba, Argentina

ABSTRACT: Argentinean loess has volume change properties that are highly dependent on moisture content. Typical loess are composed by fine sand and silt particles jointed by clay bridges and precipitated salts that form macro-pores which may undergo high volume decreases due to load or moisture content increases. Collapse of loess structure is a well-known mechanism that has been studied by many authors in the past. However, there are only few studies related with volume changes produced by the contamination with non-polar organic liquids (NAPL). Presence of NAPL is a frequent scenario due to accidental oil spills during fuel transportation and storage. This research presents an experimental analysis on the volume change behavior under zero-lateral displacement condition of Argentinean loess at natural moisture content and after inundations with a NAPL. Oedometer tests were run on undisturbed specimens of uncemented and cemented loess and silty sand under natural moisture content, and when flooded with water and NAPL. The results gave new insight on the relevant mechanisms responsible of soil collapse, including the relative importance of soil suction, clay bridges expansion and salt dissolution at particles' contacts.

RÉSUMÉ: Le lœss argentin a des propriétés de changement de volume qui dépendent fortement du contenu en humidité. Les loess typiques sont composés de particules de sable et de limon fin jointes par des ponts d'argile et de sels précipités qui forment des macro pores qui subissent des diminutions de volume importantes en raison de l'augmentation de la charge ou du contenu en humidité. L'effondrement de la structure du loess est un mécanisme bien connu qui a été étudié par de nombreux auteurs dans le passé. Cependant, il n'y a que peu d'études liées aux changements de volume produit par la contamination par des liquides organiques non polaires (NAPL). Présence de NAPL est un scénario fréquent en raison de déversements accidentels d'hydrocarbures pendant le transport et stockage de carburant. Cette recherche présente une analyse expérimentale du comportement de changement de volume dans des conditions de déplacement latéral nul du loess argentin à contenu en humidité naturelle et après des inondations avec un NAPL. Des tests d'odomètre ont été effectués sur des spécimens non perturbés de loess non cimenté et cimenté et de sable limoneux sous un contenu en humidité naturelle, et lorsqu'ils étaient inondés d'eau et de NAPL. Les résultats ont donné un nouvel aperçu des mécanismes pertinents responsables de l'effondrement du sol, y compris l'importance relative de la succion du sol, de l'expansion des ponts d'argile et de la dissolution du sel au contact des particules.

KEYWORDS: collapse, contamination, loess, unsaturated soil, kerosene

1 INTRODUCTION.

The behavior of loess has been widely studied in the past 60 years all around the world. The study of this type of soil gained importance because of its particular volume change behavior and the wide continental extension covered by this type of soil. Loess covers around 10% of the continental land area. Several countries including United States, Argentina, Russia, China, France, Germany, and New Zealand have important extensions of loess deposits (Rogers et al. 1994; Li et al. 2016). For instance, loess covers around 600,000 square kilometers of the Chaco-Pampean plain in the central region of Argentina (Iriondo 1997). Loess formations are frequently related to a multistage transport mechanism, involving fluvial and aeolian processes (Zárate 2003, Torre et al. 2019).

Francisca (2007) characterized the typical mechanical behavior of different Argentinian loess by using oedometers and standard penetration tests data. Uncemented loess presented no collapse upon saturation, but an important vertical deformation increase when loaded. Another group of loess developed collapse upon saturation and significant increases of vertical strains when loaded. Cemented loess showed a stress-strain relationship that showed the negligible influence of saturation. The microstructures of loess and the presence of cementation are the most important characteristics affecting its mechanical behavior. Uncemented loess presents a metastable structure characterized by a high void ratio. This type of soil is composed for fine sand, and silt particles jointed by clay bridges and precipitated salt crystals forming very large pore bodies (Rinaldi et al. 1998; Francisca 2007). The increase of water content reduces matric suction, weakens bridges between clay particles, and dissolves precipitated soluble salts. Because of that, soil structure weakens developing important volume changes when loaded (Fedda 1988; Francisca 2007, Rinaldi et al. 2007).

The mechanical behavior and physical properties of loess soils depend on the degree of saturation and presence of contaminants. Thus, particle fluid interaction and soil suction may have an important impact on the behavior of shallow and deep foundations as well as on the settlement behavior of oil tanks and pipelines.

In the last two decades, several authors analyzed the influence of oil contamination on soil mechanical and physical properties. Changes in soil properties can be attributed to physical and/or physicochemical interaction between particles and pollutants (Khodary 2018). The mechanical behavior of contaminated soil is highly dependent on soil and contaminant properties. The most relevant properties of contaminants affecting soil behavior are viscosity and density in the case of organic contaminants and ion concentration and valence for inorganic contaminants (Montoro & Francisca 2019; Francisca & Montoro 2021)). Important soil properties controlling particle fluid-interactions include plasticity, specific surface, fine particles content, and fabric (Montoro & Francisca 2010). Physical interactions between contaminants and soils prevail in coarse soils due to the relevance of mass forces, while physicochemical interactions are responsible for the behavior of contaminated fine-grained soils (Singh et al. 2009).

Several authors reported that coarse-grained soils contaminated with oil show an increase of compressibility and a reduction of the constrained modulus (Al-Sanad et al., 1995, Puri, 2000, Singh 2009). These changes were mainly attributed to the lubrication of particle contacts which also reduced friction angle (Abousnina, 2015). Thus, the bearing capacity of foundation on contaminated coarse soils reduces and the related settlement increases (Shin et al., 1999, Nasr, 2009).

Behavior of fine grained soils develops important changes when hydrocarbon contaminants became in contact with them. Particle-fluid interaction mechanisms and its effect on electric double layers (EDLs) are responsible for these changes. Thickness of the EDL decreases when NAPLs are in contact with fine soils given the very low dielectric constant of this contaminants. Then, net repulsive forces between particles reduce, soil fabric tends to form flocculated arrays (Kaya and Fang 2000, Nasehi et al., 2016, Francisca and Montoro 2021), liquid limit reduces, and hydraulic conductivity rises (Khamehchiyan et al., 2007, Montoro and Francisca 2010).

The presence of NAPL in fine grained soils also affects their mechanical properties (strength and volume changes). Nasehy et al. (2016) tested clayey soils and observed that the compression index increased and coefficient of consolidation reduced due to the contamination with organic liquids. Similar trends were reported by Meegoda and Ratnaweera (1994), Chen et al. (2000), Khamehchiyan et al. (2007), Singh et al. (2008), Di Matteo et al. (2011), Khosravi et al. (2013) and Estrabragh et al. (2016). However, there is limited information on the effect of NAPL on the recompression/swelling index of fine grained soils. The effect of oil contamination on the behavior of collapsible soils has been little studied. Francisca et al. (2015) analyzed the response of loess samples in contact with non-polar fluids under zero lateral displacement condition. They concluded that loess samples develop reduced collapse when in contact with NAPL in comparison with the expected behavior when the flooding liquid is water.

The main objective of this research is to understand the mechanisms responsible for the volume changes observed in loess due to the contamination with NAPL.

2 MATERIALS AND METHODS

Eight loess samples were collected from different excavations located in Cordoba City in Argentina. Sampling depth was 1 m in all cases. The main physical properties of tested samples are: natural water content between 6.1 and 21.3%, passing sieve #200 above 86%, dry unit weight from 12.1 to 13.9 kN/m^3, the liquid limit between 22.3 to 25.3%, and plasticity index from 1.0 to 4.6%.

Three oedometer tests were performed for each specimen, one at natural moisture content, the other flooded with water, and the last one flooded with kerosene. Tested samples were 63.3 mm in diameter and 25.3 mm in height. Yielding pressures, compression, and recompression indexes were determined from the compressibility curves (semi-log scale).

3 RESULTS AND DISCUSSION

Fig. 1 shows three typical behaviors for the compressibility curves at natural scale obtained from the oedometer tests performed at natural moisture content, flooded with water and with kerosene. Fig. 1a shows the change of void ratio in terms of the increase in the applied vertical pressure for uncemented loess. This sample presents a drastically increase in compressibility after water inundation, this behavior is typical for loess soils as was previously reported by many authors (Francisca, 2007; Rinaldi et al, 2007). Negligible differences were measured in the resulting void ratios when tested at natural moisture content and flooded with kerosene. These results indicate that kerosene cannot modify the loess microstructure of this type of loess even is fully saturated with two non-miscible liquids (water and kerosene). Fig. 1b shows a typical result for loess where compressibility increases after inundating them with either water or kerosene, being the effect significantly more important in the case of water. Then, differences in the stress-strain behavior are expected due to the presence of kerosene. This behavior is typical of the loess with large macropores and unstable microstructure, frequently designed as self-collapsing loess. Fig. 1c shows typical results obtained for cemented loess according to Francisca (2007). In this type of loess, no variations are expected when flooded with kerosene given that the mechanical behavior is controlled by cementation.

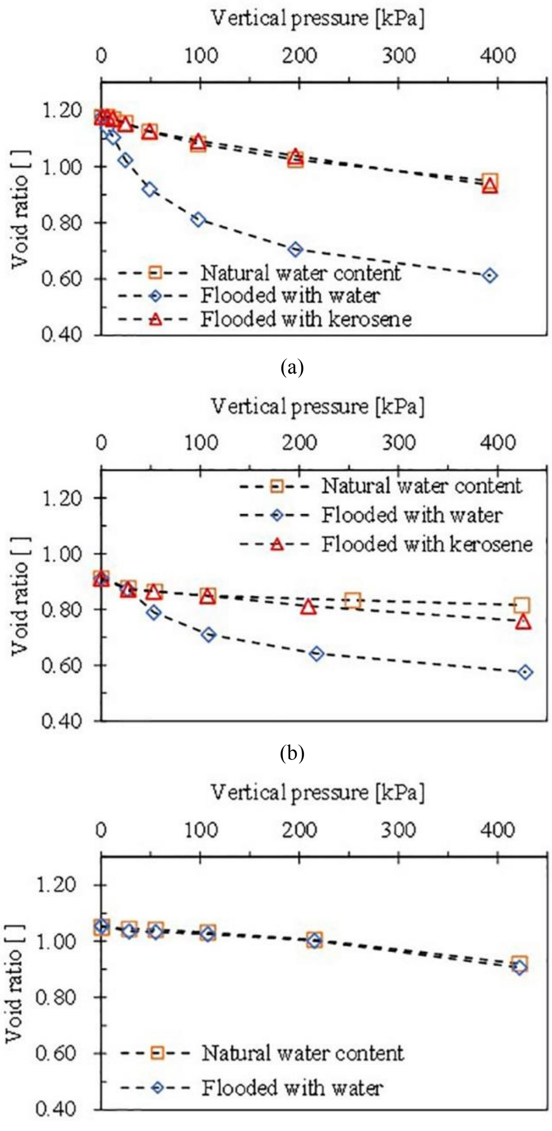

Figure 1: Compressibility curves of loess at natural water content, inundated with water and with kerosene. a, b and c) uncemented loess.

Fig. 2 shows the relationship between the compression index of the specimens flooded with water and those determined at natural water content and inundated with kerosene. A 1:1 line is also plotted in Fig.2 for direct visual reference. In general, Cc was lower for the samples tested with water than for the twin sample tested with kerosene and at natural moisture content. Small differences were obtained in these last two testing conditions (red triangles are closer to the equality line in Fig. 2). Thus, loess soils are slightly stiffer at natural moisture content than flooded with kerosene, and considerably stiffer than when flooded with water.

The trends shown in Figure 2 are opposite to the ones reported by Chen et al. (2000). The results obtained in this research can be explained based on the macro and microstructure features of loess. Samples tested had a very rigid granular skeleton at natural water content, however, when inundated with kerosene a suction decrease is expected given that soil pores are simultaneously occupied by water and kerosene. This reduction in suction is related to the lower interfacial tension of water-kerosene in comparison with the air-water surface tension. This reduces capillarity effects in the specimens saturated with two non-miscible liquids (Francisca et al., 2003; Rinaldi and Francisca, 2006), and also explains the higher compressibility of specimens saturated with water (with no menisci inside the pores) (Giomi & Francisca, 2021).

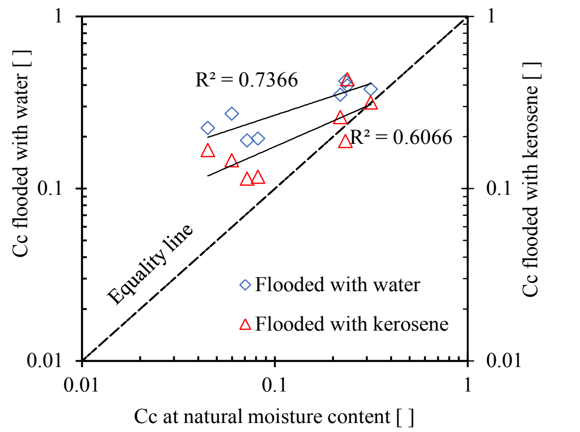

Figure 2: Scatter plot of compression indexes for samples at natur al water content and flooded with kerosene versus the compressio n indexes for samples flooded with water.

Fig.3 presents the relationship between the recompression indexes Cr determined for the loess tested at natural moisture content, and flooded with kerosene and water. Values very similar to each other were obtained, with negligible differences in the case of specimens tested at natural moisture content and flooded with kerosene. In this case, this effect can be attributed to low and similar microstructure changes during the load increase in the oedometer tests. Also, no collapse at low pressures was observed in all samples flooded with kerosene, as previously shown by Francisca et al. (2015).

The Cr of the specimens with a very high initial void ratio changed when they were flooded with water. This can be attributed to permanent changes in soil fabric that take place because of the collapse of soil microstructure (Francisca 2007, Li et al. 2016). In all other cases, Cr remains almost constant regarding the fluid and degree of saturation. Khosravi et al. (2013) obtained similar results for kaolinite clay samples tested with gas-oil fuel.

Figure 4 shows the relationship between the yielding pressure (Pf) determined for the specimens flooded with water and those determined at natural moisture content and flooded with kerosene. Note that yielding pressure in case of specimens saturated with water is known as preconsolidation pressure.

The results show important reductions in Pf when the specimens were flooded with water. All yielding/preconsolidation pressures determined for the specimens saturated with water were lower than 50 kPa. Conversely, Pf when flooded with kerosene resulted higher than when flooded with water, but with significant deviations in comparison with the expected behavior at natural moisture content.

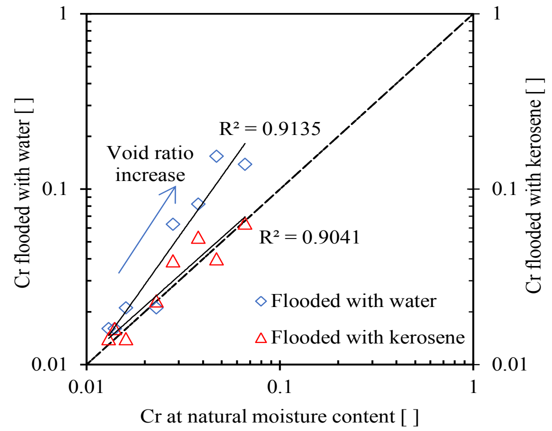

Figure 3: Scatter plot of recompression indexes for samples at natural water content and flooded with kerosene versus the recompression indexes for samples flooded with water.

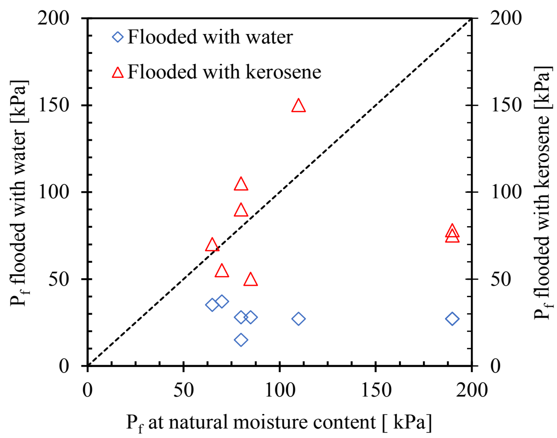

Figure 4: Scatter plot of the yielding pressure at natural water content and kerosene inundated conditions versus the yielding pressure obtained for samples under water inundated conditions.

The results show that the mechanical behavior of loess is modified by the presence of non-polar liquids, as the kerosene used in this research. Thus, the volume changes of collapsible soils in contact with hydrocarbons should be considered in foundations and oil pipelines design and analysis.

4 CONCLUSIONS

This work presents experimental results of confined compression tests under zero lateral displacement (oedometer tests) performed in loess from Argentina. Tests were performed in samples at natural moisture content, flooded with water, and flooded with kerosene.

Uncemented loess samples present collapsible behavior, and an increase in compressibility when flooded with water. The presence of kerosene does not produce collapse at low pressures (Francisca et al. 2015) but increases the compressibility of loess.

Compression and recompression indexes of loess are controlled by the saturation liquid inside the pores. Cc significantly increases due to the presence of water and in less proportion due to the presence of hydrocarbons. Cr is slightly affected by the water saturation and no measurable differences are expected due to the presence of hydrocarbons. Increases of Cr in samples flooded with water were detected only for loess with a high initial void ratio. This trend was associated with permanent changes of loess microstructure expected when water content increases and therefore soil collapse take place.

Yielding pressure is significantly reduced upon saturation with water, with values between 10 kPa and 50 kPa. Loess flooded with kerosene show no significant reductions in yielding pressure but the variability of results increases meaning that other relevant particle-fluid interaction mechanisms may take place.

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