Research Article

Qasim A. Al-Obaidi* and Tom Schanz

Deformation of unsaturated collapsible soils under suction control

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Abstract: Collapsible soils present significant geotechnical and structural engineering challenges worldwide. They can be found in arid or semi-arid regions and are directly affected by the multi-step wetting procedure due to the reduction of soil suction. The main objectives of this paper are to investigate the volume change behaviour, collapse mechanism and deformation characteristics under the control of suction and net vertical stress. In this study, three types of collapsible soils were investigated such as natural soils of sandy gypseous, silty loess, and artificial soil of gypsum–sand mixture. A series of constant net stress-suction control (wetting and drying) tests using a combination of axis-translation and vapor equilibrium techniques were deployed to cover a wide range of applied suction. The test results show that large volume change and collapse deformation occur upon a stepwise suction decrease. On the other hand, shrinkage behaviour resulting from increases in imposed suction is observed during the drying path. The collapse deformation depends on the stress path and is a function of net normal stress, suction, dry density, and degree of saturation. The water content and the degree of saturation dramatically increase as the applied suction decreases from the initial high to zero values at the drying path.

Keywords: collapse potential, negative pore water pressure, suction, unsaturated, loess, gypseous

*** Corresponding author: Qasim A. Al-Obaidi,** Civil Engineering Department, University of Technology, Baghdad, Iraq, e-mail: qasim.a.jassim@uotechnology.edu.iq
Tom Schanz: Chair of Soil Mechanics, Foundation Engineering and Environmental Geotechnics, Department of Civil and Environmental Engineering, Ruhr-Universität Bochum, Bochum, Germany, e-mail: tom.schanz@rub.de

1 Introduction

Collapsible soil is one of the problematic soils that present severe geotechnical and structural engineering challenges during and after the construction of engineering structures. The most common definition of collapsible soils is, "Any unsaturated soil of a metastable structure that goes through a radical rearrangement of particles and great loss of volume upon wetting and reduction in matric suction with or without additional loading" [1–3]. The collapse potential (I_c) can be calculated according to the formula by [4] as follows:

$$I_c = \frac{e_1 \quad - e_2}{1 + e_o} \times 100, \tag{1}$$

where I_c is the collapse potential (%), e_1 is the void ratio at dry condition, e_2 is the void ratio at a saturated condition, and e_o is the natural void ratio

However, a substantial precondition is that an open metastable structure or open porous fabric is developed through different bonding mechanisms. Bonds between the soil particles can be created *via* capillary forces (*e.g.* suction) and/or by cementing materials (*e.g.* clay or salts) [5]. Moreover, when the vertical stresses in non-plastic soils exceed the yield strength of these bonding materials, especially under wet conditions, collapse or deformation suddenly occurs [3,6].

Gypseous soil is one type of collapsible soils and it has low dry density and moisture content in its natural state due to the presence of cementation bonds and an open gypsum structure. Moreover, soil deformation occurs as a result of the dissolution of the cemented gypsum bonds within the soil mass [7–9].The chemical composition of the gypsum is $CaSO_4{\cdot}2H_2O$, the specific gravity is 2.32, and the solubility ranges between 2.0 and 2.5 g/L [10,11].

Loess soil is one of the most widespread formations of the ice age and covers about 10% of the earth's surface. Loess is formed by silt-sized (*e.g.* typically 20–30 μm) primary quartz particles that are created by high-energy earth surface processes such as glacial grinding or cold climate weathering [12].

The classically unsaturated soil is considered to have four phases: solid, water, air, and air–water interface.

Soil suction is a general term commonly associated with unsaturated soil mechanics and may be used when referring to matric suction, osmotic suction, or total suction [13,14]. Thus, the relationship between the suction types can be formulated as follows:

$$\psi_t = (u_a - u_w) + \pi, \quad (2)$$

where ψ_t is the total suction, $(u_a - u_w)$ is the matric suction, u_a is the pore-air pressure, u_w is the pore-water pressure, and π is the osmotic suction.

In arid or semi-arid regions having low rainfall intensity, the wetting process of subsurface layers is normally due to the gradual rising of ground water by capillary forces. This fact should be taken into consideration when estimating the volume change behaviour of collapsible metastable-structured soil. The collapse potential calculated by the full wetting process of the soil layer may not be achieved in the field due to the inability to reach a complete saturation of the soil deposit by single-step wetting. Therefore, it is important to investigate the effect of the progressive wetting process by stepwise reduction of the imposed suction pressure on the collapsible soil sample, as well as to evaluate the relationship between the critical values of the collapse potential corresponding to the magnitude of applied suction. Therefore, the main objectives of this paper are to investigate the volume change behaviour and collapse deformation mechanism of collapsible soils under the control of suction pressure and net normal stress.

2 Materials, equipment, and techniques

2.1 Soil samples

Three types of collapsible soils were investigated: gypseous sand soil from a semi-arid region of Al-Ramadi city, west of Iraq, denoted GI; loess silt soil from Dresden City, east of Germany, denoted LG, and an artificial sample of 70% gypsum–30% Silber sand mixture, denoted 70G30S. The summary of the physical properties of the soil samples is given in Table 1.

2.2 Equipment and techniques

In order to perform the constant net normal stress-suction control (wetting and drying) tests, a combination of two techniques was used to cover a wide range of imposed suction.

2.2.1 Barcelona cell

The Barcelona cell is a one-dimensional compression Oedometer with the axis-translation technique (ATT), as shown in Figure 1. The vertical stress is uniformly applied to the soil specimen by air pressure using a flexible membrane. The diameter of the specimen ring is 50 mm, and the height is 20 mm. The main function of this cell is to measure

Table 1: Summary of physical properties of the soil samples

Property	Gypseous soil GI	Mixed soil 70G30S	Loess soil LG	Standard
Atterberg's limits: LL, PL, PI (%)	NP	NP	28.2, 16.8, 11.4	ASTM D4318
Specific gravity (Gs)	2.35	2.4	2.63	ASTM D854
In place dry density (g/cm^3)	1.3	—	1.6	ASTM D2937
Standard compaction test				
Max. dry density (g/cm^3)	1.7	1.69	1.74	ASTM D1557
Opt. moisture content (%)	8.0	12.9	16.4	
Natural void ratio e_o	0.81	—	0.64	
Particle size analysis				
Cu	11.58	19.4	—	ASTM D422
Cc	0.33	0.16	—	
Passing sieve size (75 μ) (%)	22.1	35.5	98	
Initial suction ψ_o (kPa)	139,280	198,016	111,311	Chilled-mirror Hygrometer
Gypsum content (%)	70	70	0	Al-Mufty and Nashat [15]

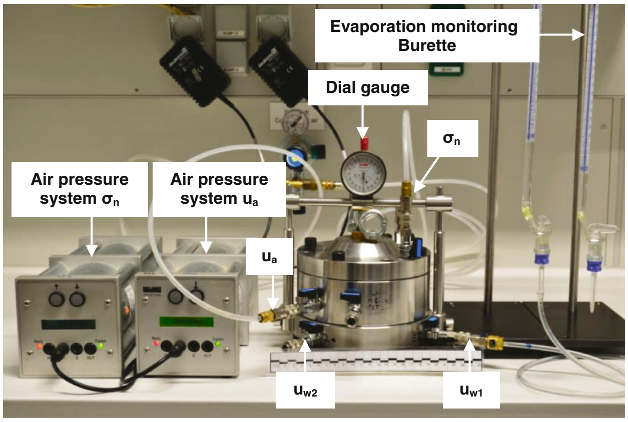

Figure 1: Barcelona cell with the ATT.

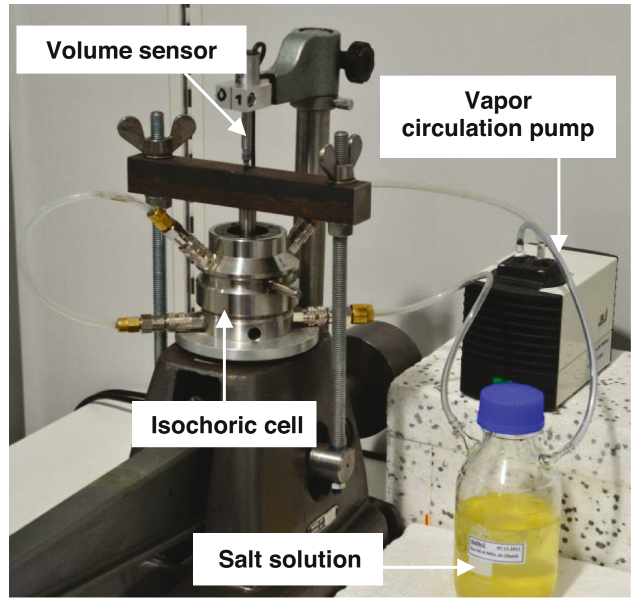

Figure 2: Modified-Isochoric Oedometer cell with the VET.

the volume change of the soil sample resulting from the variation of matric suction followed by the wetting or drying stress paths under the effect of one-dimensional net normal stress (σ_n). The ATT was utilized through a high-air-entry ceramic disk (100, 500, and 1,500 kPa) provided in the base plate of the cell below the soil specimen. The Barcelona cell is connected with a high-accuracy burette, one air-pressure system for the application of matric suction, and one air-pressure system for the application of net normal stress.

2.2.2 Modified-Isochoric Oedometer cell

The isochoric cell is based on the vapor equilibrium technique (VET) and used for applying total suction of more than 2,000 kPa as shown in Figure 2. The cell consists of three main parts: an exchangeable pedestal, a threaded top part with a top cap, and a load cell for measuring the swelling pressure. The diameter of the specimen ring is 50 mm and the high is 20 mm. The isochoric cell was modified to utilize the Oedometer frame in order to estimate the soil volume change resulting from suction variation under constant net normal stress. The cell was "calibrated" based on pressure deformability and the exact surcharge weight of each test. The changes in the water content of the soil specimen due to total suction variation were controlled by directly weighing the Isochoric cell body after each step of suction. The initial conditions of the soil samples and the boundary conditions of the test are given in Table 2. The tests were carried out in the Laboratory of Soil Mechanics, Chair of Foundation Engineering and Environmental Geotechnics, Ruhr Universität Bochum, Germany. The Barcelona cell and isochoric cell were designed by University of Polytechnic of Catalonia (UPC) and used by many researchers such as [16] and others.

3 Results and discussion

3.1 Constant net normal stress-suction decreases (CN-SD) wetting test

Figure 3 indicates the relationship between void ratio (e) and net vertical stress (σ_n), all soil samples presented low compressibility when loaded under unsaturated

Table 2: Initial conditions of the soil samples and the boundary conditions of the test

Soil type	(CN-SD) wetting test				(CN-SI) drying test			
	e_o	γ_d (g/cm^3)	Sr (%)	ψ_o (kPa)	e_o	γ_d (g/cm^3)	Sr (%)	ψ_o (kPa)
Gypseous soil (GI)	0.81	1.3	0	139,280	0.81	1.3	100	0
Mixed soil (70G30S)	0.81	1.3	0	198,016	0.81	1.3	100	0
Loess soil (LG)	0.64	1.6	10	111,311	0.64	1.6	100	0

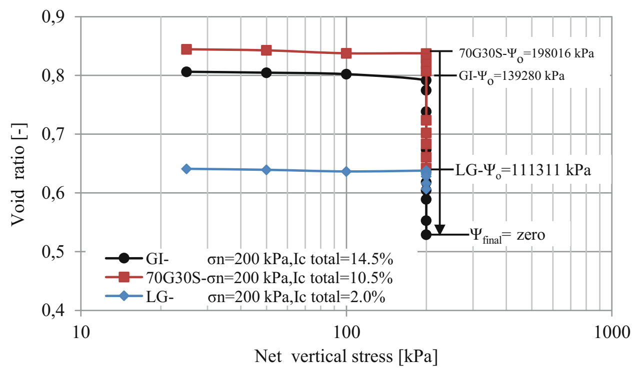

Figure 3: Variation of the void ratio with net vertical stress of the (CN-SD) wetting test.

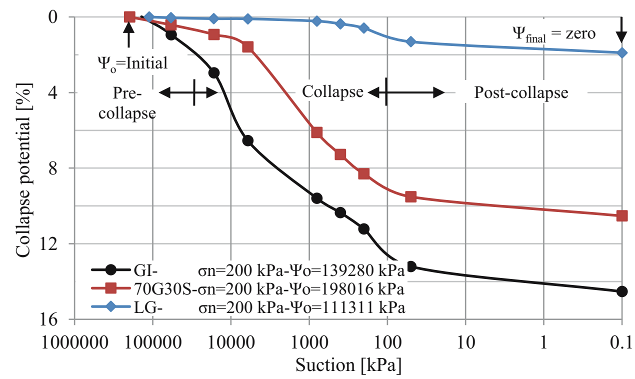

Figure 5: Variation of the collapse potential with suction of the (CN-SD) wetting test.

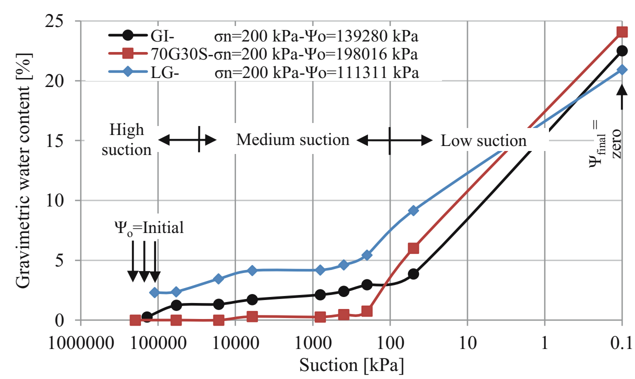

Figure 6: Variation of the gravimetric water content with suction of the (CN-SD) wetting test.

conditions (*i.e.* at their initial suction ψ_o). Upon multi-step wetting by suction decreases under constant net vertical stress, the volume change during the suction-equilibrium stage of soil is denoted collapse deformation.

Figures 4–7 demonstrate the variations in the collapse potential (I_c), void ratio (e), gravimetric water content (w), and degree of saturation (Sr) with applied suction (ψ). The measured values of the void ratio decreased (Figure 4) and the collapse potential increased (Figure 5) progressively due to a reduction in applied suction under the wetting path. In other words, maximum collapse deformation can be observed under zero suction.

However, Figures 4 and 5 indicate that the loess soil (LG) did not present significant collapse behaviour when the suction was reduced, as in the case of gypseous soils. However, insignificant swelling with relative increases in the void ratio was observed in the first stage of wetting when the applied suction ranged between ψ = 6,100 and 50 kPa, w = 5–15%, and Sr = 19–61%. The swelling could be attributed to the decrease in mean effective stress resulting from the reduction in matric suction, which in turn led to a relative increase in the void ratio. Moreover, the collapse potential reached more than 12% of its final value when ψ = 800 kPa, w = 4–5%, and Sr = 17–21%; and more than 70% when ψ = 50 kPa, w = 9–11%, and Sr = 39–49% (see Figures 5–7). For gypseous soil GI, the collapse potential reached more than 60% of its final value when the suction decreased to ψ = 800 kPa (see Figure 5), where the gravimetric water content (w)

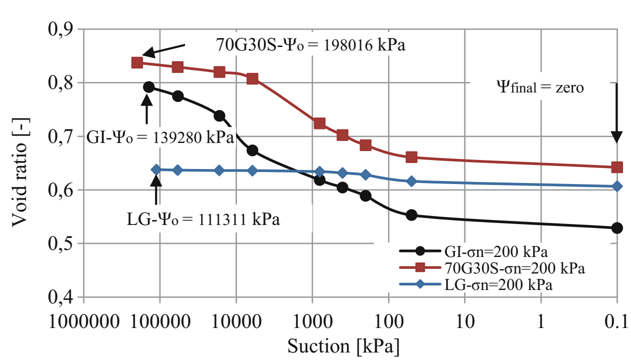

Figure 4: Variation of the void ratio with suction of the (CN-SD) wetting test.

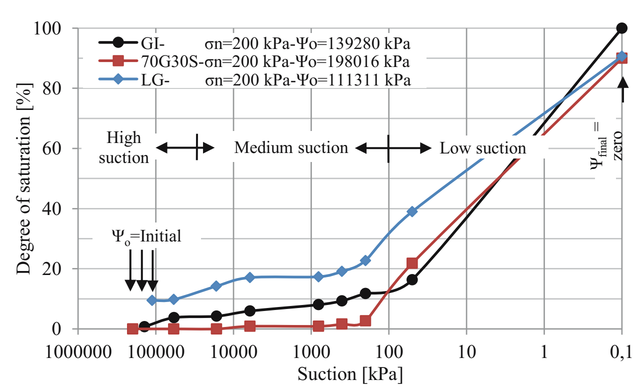

Figure 7: Variation of the degree of saturation with suction of the (CN-SD) wetting test.

and the degree of saturation (Sr) ranged 1.5–2.5 and 6–8.5%, respectively (see Figures 6 and 7). Likewise the collapse potential exceeded 85% of its final value when the suction was reduced to ψ = 50 kPa corresponding to the range of w = 3.5–5% and Sr = 11–29% as shown in Figures 5–7. This behaviour was the same for the artificial gypseous soil (70G30S) when the samples were loaded under a value of net vertical stress equal to 200 kPa (see Figures 5–7). The collapse was 58% of its final value at ψ = 800 kPa, w = 0.3%, and Sr = 1, and 90% of its final value at ψ = 50 kPa, w = 6%, and Sr = 22% (see Figures 5–7).

In other words, three main distinct phases are developed in the collapse mechanism of the tested soils: the pre-collapse phase, the collapse phase, and the post-collapse phase [17]. In the pre-collapse phase, insignificant collapse deformation occurred with respect to a relatively large decrease in the value of imposed suction. This behaviour can be attributed to the action of cementing bonds between soil particles. The devaluation of the suction at that stage may stimulate gypsum–sand and clay–silt bonds, which start softening in place without any movement or deformation. Therefore, this action was insufficient to cause collapse deformation in the soil structure. This behaviour can be attributed to the elastic compression of the soil structure without grain slippage. This phase of deformation arose at high suction ranges (*i.e.* ψ = 50,000 kPa for GI and 70G30S, ψ = 10,000 kPa for LG, see Figure 5).

The collapse phase occurred at intermediate ranges of suction (*i.e.* ψ = 100–50,000 kPa for GI and 70G30S, ψ = 100–10,000 kPa for LG, see Figure 5) and could be recognized due to significant volume change and collapse deformation. This deformation was induced after only a few hours of the suction reduction, and it continued until the soil suction reached equilibrium at the microstructure level. These findings agreed with the results of [18,19].

Moreover, for both GI and 70G30S soils, the gypsum bonds that connected the soil particles tended to be removed or softened after the disappearance of the suction resulting in collapse.

For LG soil, the collapse occurred as a result of the dispersion and disruption of silt–clay bridges or buttresses between loosely packed silt grains leading to the initial rapid collapse of the inter-particle matrix. At the macrostructure level, collapse deformation occurred as a result of the grains densifying and rearranging into a more closely packed structure after the cavities had crashed and had been destroyed by stress redistribution over time. These results are confirmed by the results obtained by [20]. In the third phase (*i.e.* post-collapse), the volume change commonly occurred at a low suction range (*i.e.* ψ = 100 kPa), and it was characterized by small volumetric deformations as a response to a further reduction in suction after reaching nearly full saturation. This deformation occurred because of secondary compression (*i.e.* creep) of the softened soil mass especially for GI and 70G30S soils. The test results also indicated that the gravimetric water content (Figure 6) and the degree of saturation (Figure 7) similarly increased as the suction of the soil was reduced from the initial value to zero, irrespective of the differences in soil collapse caused by different net vertical stresses. In other words, when the amount of water in the soil sample increased at a low suction range (*i.e.* ψ = 100 kPa), the volume of air in the pore space decreased due to pore collapse. These results also showed that it was not possible to reach a fully saturated soil sample at zero suction, especially at low values of net vertical stress because the soil structure still contained some air bubbles trapped. From the previous discussion, it can be concluded that the collapse deformation of collapsible soils was considerably stress path-dependent and was a function of net normal stress, suction, and the degree of saturation. However, the changes in the volume of collapsible soils corresponded mostly to the changes in the degree of saturation and suction. Full saturation of the soil sample was not necessary to achieve final collapse, as shown in Figure 8. In other words, partial saturation to a degree lower than 30% for gypseous soils and 50% for loess soil could introduce the final value of the collapse potential, particularly at low suction ranges regardless of net vertical stress between the gypseous soils particles and greater than the maximum preconsolidation pressure for loess soil.

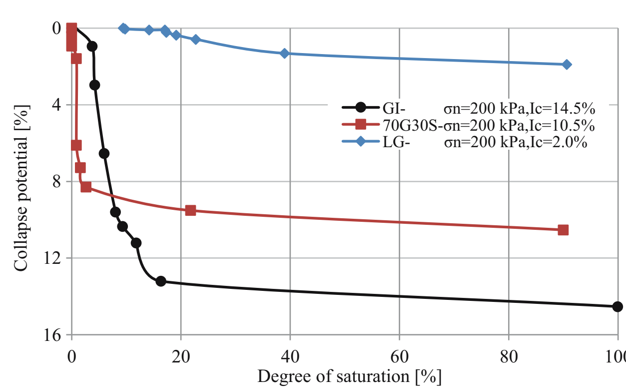

Figure 8: Variation of the collapse potential with degree of saturation of the (CN-SD) wetting test.

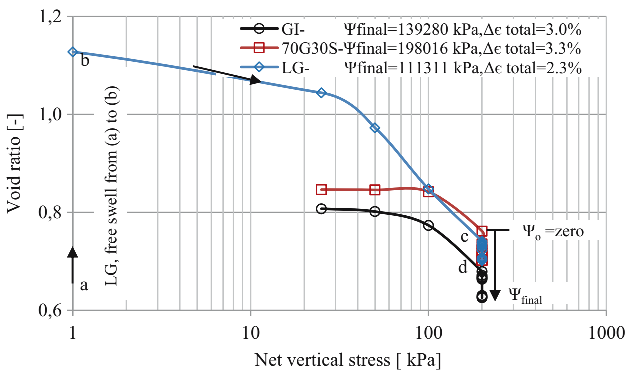

Figure 9: Variation of the void ratio with net vertical stress of the (CN-SI) drying test.

3.2 Constant net vertical stress-suction increases (CN-SI) drying test

Figure 9 shows the relationship between the void ratio and net vertical stress. Figures 10–13 demonstrate the variations in the volumetric strain, the void ratio, the gravimetric water content, and the degree of saturation with applied suction, respectively.

In order to achieve a fully saturated state, the soil sample was allowed free access to water and free swelling (when the soil structure has the potential to swell) without any loading condition.

The compression stage was started after the saturation stage, where $\psi = 0$ by increasing the loading stepwise until the target constant net vertical stress was reached (*i.e.* $\sigma_n = 200$ kPa, $\psi = 0$). Then, the sample followed the drying path (*i.e.* suction increases) until the final suction (ψ_{final}) was reached, which corresponded to the initial suction value of the soil under constant applied net vertical stress (*i.e.* $\sigma_n = 200$ kPa, ψ_{final} is the value of initial suction).

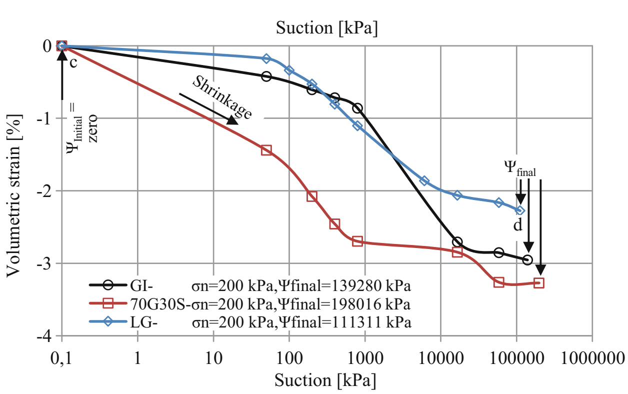

Figure 10: Variation of volumetric strain with suction of the (CN-SI) drying test.

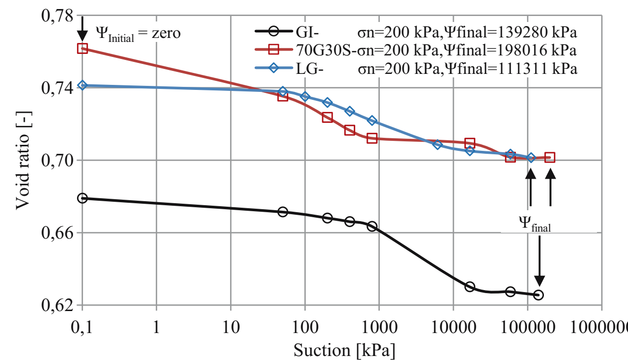

Figure 11: Variation of the void ratio with suction of the (CN-SI) drying test.

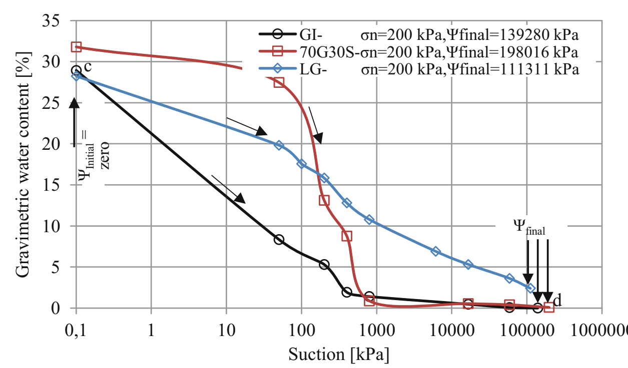

Figure 12: Variation of the gravimetric water content with suction of the (CN-SI) drying test.

For naturally gypseous and artificially gypsified soils, no swelling was recorded as expected. Loess soil presented considerable swell potential where the void ratio increased significantly from point a to point b, as shown in Figure 9. The drying path for the three selected soils was started at a fully saturated state (*i.e.* $\psi_o = 0$; point c in Figure 9) and when no further settlement was recorded

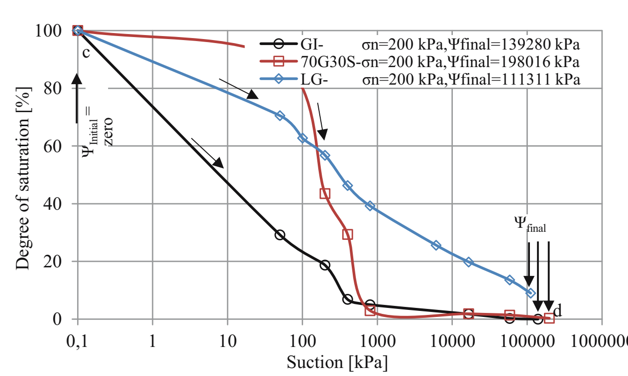

Figure 13: Variation of the degree of saturation with suction of the (CN-SI) drying test.

under a constant net vertical stress of 200 kPa at a saturated state.

The drying process was carried out by a multi-step increase of applied suction. Under such conditions, the soil sample was subjected to a volumetric change that can be interpreted as a soil settlement due to the reduction in void ratio by the shrinkage phenomenon, as shown in Figures 10 (points c and d) and 11.

The fact signified that this deformation did not occur as a result of the collapse deformation but because of the shrinkage strain of the soil mass particularly at high net vertical stress, see Figure 11. This behaviour could be related to the fact that the entrapped air bubbles created by increasing the imposed suction replaced the water molecules in the pore space. Figures 12 and 13 demonstrate the great reduction that occurred in the values of gravimetric water content and the degree of saturation as a result of an increase in applied suction.

4 Conclusions

1. The final collapse volume change in soil resulting from the multi-step wetting procedure is a function of the initial void ratio, initial degree of saturation, and initial suction.
2. Three main distinct phases for collapse mechanism, namely, pre-collapse, main collapse, and post-collapse, over the suction range are observed for all tested collapsible soils.
3. The main collapse deformation of more than 70% of total collapse has occurred at a medium range of soil suction (*i.e.* 100–10,000 kPa), especially for gypseous soil.
4. Under a low range of applied suction (≤100 kPa), the final soil collapse is reached after a few hours of wetting and at a degree of saturation of 30–50%. After the final collapse, a creep deformation in gypseous soils is observed, while it was negligible in loess soil.
5. No collapse behaviour for the loess soil was observed under the suction value lower than the maximum preconsolidation pressure. However, insignificant swelling with relative increases in the void ratio was observed under the medium suction range.
6. At the microstructure level and under reduction of suction, the collapse occurred due to the absence of cementing bonds for gypseous soils and as a result of the dispersion and disruption of silt-clay bridges and buttresses for loess soil.
7. At the macrostructure level, collapse deformation occurred as a result of the grains densifying and rearranging continuously into a more closely packed structure over time with a reduction of suction.
8. Full saturation of the soil with complete absence of the soil suction was not necessary to achieve final collapse. Partial saturation with about 30–40% under a low suction range of about 50–100 kPa can introduce the final collapse over a significant time period.

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