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Effect of Suction on Volumetric Yielding Behavior under Different Initial Conditions for Fine-Grained Soils

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ABSTRACT

The unsaturated soils are difficult to consider within the framework of classical (saturated) soil mechanics. In general, the unsaturated soil is stiffer than the saturated one (hardening), so the location and slope of normal consolidated line (NCL) or the volumetric yielding behavior of unsaturated soil is different from the saturated behavior. This work investigates the volumetric yielding behavior of unsaturated soil; by determine the One-dimensional normal consolidated lines (NCL's) under different suctions. Two materials namely pure Calcigel bentonite (100B) and a mixture of 30% Calcigel bentonite and 70 % Haider sand (30B) were prepared at two initial conditions (i.e. slurry and loose states). In this type of test, after reaching to the designed suction, the net stress is increased through the test while the suction is kept constant. Thirteen 30B specimens and two 100B specimens were tested under constant suction condition. The constant applied suction in this study was varied from 0 kPa till 39000 kPa because of the possibility to increase the preconsolidation pressure (yield stress) more than 24000 kPa (the maximum limit of the used one-dimensional high stress consolidation equipments). Two techniques (i.e. axis translation technique and vapor equilibrium technique) were used to apply and control suction on tests. The controlled-suction one-dimensional high stress consolidation tests results show that the position and the slope of NCL's depend on both net stress and suction. The NCL's either, for low suction value, has void ratio lower than the saturated NCL (associated with slope lower than the saturated NCL), or the NCL has void ratio higher than the saturated NCL (associated with slope higher than the saturated NCL) for higher suction value.

Keywords: Initial State, Bentonite, Unsaturated Soil, Volume Change, Yield Stress, 1D-NCL, and Suction.

تأثير اجهاد المص على السلوك الخضوع الحجمي في ظل خواص الحبيبات-اولية مختلفة للتربة ناعمة

الخلاصة

التربة غير المشبعة صعبة للنظر في إطار ميكانيك التربة الكلاسيكية (المشبعة) .بشكل عام، التربة غير المشبعة هي أشد من تلك التي المشبعة (اكثر تصلب)، وبالتالي فإن موقع وميل خط الانضمام الطبيعي(NCL) أو السلوك الحجمي للتربة غير المشبعة يختلف عن السلوك الترب المشبعة .تبحث هذه الدراسة في سلوك الخضوع الحجمي للتربة غير المشبعة, بتحديد خطوط الانضمام الطبيعي (NCL's)ذات بعد واحد تحت اجهادات مص مختلفة . وقد تمت الدراسة على نوعين من الترب وهما البنتونايت نوع Calcigel (B100) وخليط من 30 ٪ البنتونايت و 70 ٪ الرمل (B30) في ثلاثة خواص اولية مختلفة (أحالة الطين المستحلب و الحالة المفككة). في هذا النوع من الاختبار، بعد الوصول الى اجهاد المص المصمم ، يتم زيادة صافي الضغط الخارجي خلال الاختبار بينما يتم الاحتفاظ باجهاد المص ثابتاً .تم اختبار ثلاث عشرة عينة من عينات B30 وعينتين من B100 تحت حالة اجهاد مص ثابتة. في هذه الدراسة قد اختلفت قيم اجهاد المص المطبقة الثابتة من 0 كيلو باسكال حتى 39000 كيلو باسكال بسبب احتمال لزيادة إجهاد الخضوع أكثر من 24000 كيلو باسكال (الحد الأقصى لخلية الانضغاط الأحادية البعد العالية الإجهاد المستخدمة). استخدمت اثنين من التقنيات (أي تقنية انتقال المحور و تقنية التوازن بخار) لتطبيق و السيطرة على في الاختبارات. أظهرت نتائج اختبارات الانضمام ذي البعد الواحد عالية التحيمل ذات اجهاد مص مسيطر عليها أن موقع وميل خط الانضمام الطبيعي(NCL) تعتمد على كل من صافي الإجهاد و اجهاد المص . أظهرت النتائج ان خط الانضمام الطبيعي (NCL) يكون إما ,لقيمة اجهاد مص منخفضة، ذات نسبة الفراغ أقل من NCL للحالة المشبعة (متلازمة بميل أقل من ميل NCL للحالة المشبعة)، أو ذات نسبة الفراغ أعلى من NCLللحالة المشبعة (متلازمة بميل اعلى من ميل NCL للحالة المشبعة) لقيمة اجهاد مص أعلى.

INTRODUCTION

The soil forming in shallow layers in the arid and semi-arid regions and the compacted soil used in earth dams, highways, embankments, airport runways, and the sealing and buffer materials engineering barriers e.g., used for the nuclear repository are in unsaturated conditions. Whenever the water interacts with a soil that is in a state of unsaturated condition volume change may occur. Such soil-water interaction may cause collapse or swell depending on soil condition. Moreover the wetting may cause reduction of the shear strength (softening) and increase of the hydraulic conductivity. In case of increasing the suction (drying) for initially saturated soils, slurry or compacted, the resulted curve is named the soil water characteristic curve (SWCC), while in case of initial unsaturated state soils, the curve will identify as soil-water retention curve (SWRC).

The classical principles and concepts of soil mechanics for saturated soil are often not suitable for describing such problems, [1]. The sum of two components (i.e., matric suction, s, and osmotic suction, π) is called total suction, s_t. The matric component is related to the difference between pore-air pressure (u_a) and pore-water pressure (u_w) in the soil (the air-water interface or surface tension) giving rises to the capillary phenomenon. The osmotic suction component is related to the dissolve solutes in bulk water which is defined as the “free water”.

Currently, there are two approaches to describe the unsaturated soil behavior (volume change and the shear strength behavior): the effective stress approach (Bishop, 1959) [2] and the two independent state variables approach (Fredlund and Morgenstern, 1977) [3].

Effective stress approach: [4]; [2]; and [5] all proposed modified forms of effective stress equation (Equation 1) to account for the two-phase nature of the pore fluid in the unsaturated soil.

$$s' = (s - u_a) + c(u_a - u_w) \qquad \ldots (1)$$

Where s' = effective stress; s = total stress; u_a = pore air pressure; u_w = pore water pressure; c = effective stress parameter, which has a value of 1 for saturated soils and 0 for dry soils.

Two independent stress variables approach: [3] proposed the state of stress in unsaturated soils to be describe in terms of two independent (two independent stress variables), namely (s - u_a), at the macroscopic scale and (u_a - u_w) at the pore scale, to avoid the introduction of a material parameter in the effective stress equation. A separate set of material properties was then introduced for each of the stresses.

MATERIAL USED and SAMPLES PREPARATION

The materials used in this study are pure bentonite 100B and a mixture of betonies and quartz sand, 30% bentonite and 70% sand mixture 30B [6].

The bentonite and sand mixtures with compositions of 30% bentonite and 70% sand (30B) and pure bentonite (100B) were prepared. The bentonite was mined from Bavaria, Southern part of Germany. Table 1 summarizes the properties of bentonite and sand used in this study based on ASTM standards, [7] and DIN standards, [8]. The Liquid limit for (30B) mixture is 30% and for pure betonies (100B) is 89. The slurry soil was prepared by mixing the soil with water equal to 1.1 of liquid limit (L.L.).

To cover all the possible states of unsaturated volume change, the initial conditions of the specimens used are divided into two states: ((i) Slurry (Sl) when drying path was applied and (ii) Loose (Lo) when wetting path was applied. The initial slurry state was used to study the unsaturated volume change of drying path, whereas the initially loose state was used to study the unsaturated volume change of wetting path. The slurry specimens were prepared by mixing the soil with water content equal to 1.2 times its liquid limit (i.e., 36 % for 30B and 107 % for 100B). The soil was mixed daily for at least one week to produce homogonous mixture. The loose specimens were prepared to produce maximum void ratio of unsaturated state. Water content of range (65 %-10%) to achieve suction ranges (12 MPa-3.5 MPa) brings into being maximum initial void ratio for 30B soil and water content 24 % to achieve suction 10 MPa produces maximum initial void ratio for 100B soil.

EXPERIMENTAL PROGRAM

The study amides to investigate the effect of suction on volumetric yielding behavior under different initial conditions for fine-grained soils. Therefore, in this type of test, the net stress is increased through the test while the suction is kept constant. Thirteen 30B specimens and two 100B specimens were tested under constant suction condition. The initial states for constant net stress test and the stress paths for each test in (net stress-suction) space are shown in Table (2) and Figure (1), respectively.

The following nomenclatures will be used as abbreviation in this work for the mixture percent, type of test, initial condition (e.g. 30B-S39-Sl = 30B mixture with 39000 kPa constant suction test for slurry initial condition): **30B** = 30% bentonite (calcigel) and 70% sand; **100B** = 100% bentonite (calcigel); S**X** = constant suction test of **X** MPa; **Lo** = loose initial state; **Sl** = slurry initial state.

The tests 30B-S0.1-SL, 30B-S0.45-Sl, 30B-S0.05-Lo, and 30B-S0.1-Lo1 were loaded under constant suction condition then followed by wetting process (reduction in suction under constant net stress) at 0.91 MPa, 1.6 MPa, 0.92 MPa, and 0.925 MPa, respectively. The maximum constant applied suction in the cerise was 39000 kPa (30B-S39-Sl test) because of the possibility to increase the preconsolidation pressure (yield stress) more than 24000 kPa (the maximum limit of the used equipments).

The state of the applied net stress in study is mainly one-dimensional using; the modified controlled-suction oedometer cells, Figure (2), UPC-Barcelona cell, UPC-Isochoric cell, and high stress oedometer cell, Figure (3). All these cells have a specimen with the following dimensions: 50 mm diameter and 20 mm height. Only one test for each soil was carried out by applying isotropic stress using triaxial device to locate the position of isotropic normal consolidation line (iso-NCL). The specimen has dimensions 50 mm diameter and 40 mm height. The procedure followed for each test depends on the type of the test. Based on the pressure-deformation characteristic of all devices, the measured volume (i.e., dry density and void ratio) at each loading and unloading steps during the compression tests were corrected.

The axis translation technique (ATT) and vapor equilibrium technique (VET) were used to apply (control) suction in the used one-dimensional compression cells. For suction range less than 1500 kPa, the axis-translation technique (ATT) was used, while for suction higher than 2000 kPa, the vapor equilibrium technique (VET) was adopted.

EXPERIMENTAL RESULTS AND DESCSION

This section presents a widespread overview for the experimental results of the volume change test under constant suction condition for unsaturated pure bentonite (calcigel), 100B, and 30 % bentonite- 70 % sand mixture, 30B. Thirteen 30B specimens (8 specimens for initially slurry state and 5 specimens for initially loose state) and two 100B specimens (1 specimen for initially slurry state and 1 specimen for initially loose state) were tested under constant suction condition. Two different initial states were chosen to examine the effect of initial state (slurry and loose) on the volumetric yielding at unsaturated state, see Table (2) and Figure (1), respectively. The initial point is denoted as point A, whereas point B represents the beginning of applying suction. Point C represents the beginning of loading under constant suction condition, and point D represents the end of constant suction condition. In the tests (30B-S0-Sl, 30B-S4.3-Lo, 30B-S10-Lo, 30B-S39-Lo, and 100B-S0-Sl), the applied constant suction was equal to the initial suction, therefore A, B, and C correspond to the same point. Tests 30B-S0-Sl and 100B-S0-Sl, Figures (4 and 7) were tested under zero suction condition (consolidation test).

Figures (4 and 5) show the results of first group (initially slurry state) of constant suction test for 30B soil. Within these tests, all the specimens start at slurry condition (point A) then the suction increases under seated load (4-7 kPa), (point B), till reaching a specific suction value (point C). Beyond that the net stress increases under constant suction condition.

The preconsolidation pressure are 7, 200, 300, 400, 600, 800, 1000, and 8000 kPa under 0, 50, 100, 255, 300, 400, 450, and 39000 kPa constant suction conditions respectively as shown in Figure (4a). The increase in the preconsolidation pressure is due to (i) increase in the density before loading (as result of increasing the applied suction) and (ii) hardening of soil material as a result of increase in suction. Most of curves in this group (except 30B-S39-Sl test) joined the 1D-NCL as net stress increases. This behavior is attributed to increase in the degree of saturation during the loading that made the specimens reaching the saturation zone. The preconsolidation pressures, for tests with constant suction range from 0 to 450 kPa, locate on the saturated 1D-NCL and the values of these pressures increase as a result of increasing the density due to applying the suction. Note the values of the void ratio before start loading, Figure (4b). The compression curve of 30B-S39-Sl test (see Figure 4a) had undergone a high reduction in volume during the initial part of loading (between point C and 100 kPa net stress). This behavior can be attributed to separation of the sample from the confining ring due to high applied suction (39000 kPa) and the incremental response of the sample changes from oedometric to uniaxial. Therefore, initially the sample had high reduction in volume until it retain back, by filling the space between the sample and the ring with soil material due to lateral deformation, to the oedometric loading condition. As the loading increased the compression curve passed the 1D-NCL till reaching 8000 kPa net stress. Beyond this point the state of the specimen changes from over consolidated to normal consolidated (yield) state with slope higher than the slope of saturated NCL. Once the suction was applied (after point B), the compressibility of the specimens in this group followed the isotropic NCL up to 255 kPa suction. Subsequently, the slope of compression curve decreased. The results of increasing suction for initially slurry state (drying path of SWCC, [9]) show that the slope of compression lines became near to zero (no compression with increasing the suction) for suction higher than 600 kPa. The same behavior was observed in case of 30B-S39-Sl test.

The gravimetric water content, of constant suction tests for initially slurry sate, decreased as suction increased along with drying path of SWCC, Figure (4c). The gravimetric water content decreased slightly as the net stress increased for over consolidation (before the preconsolidation pressure). The reduction in the gravimetric water content during the loading at the over consolidated state is believed to be due to change of the state from drying path (due to increasing the suction before loading) to wetting path (due to increase in the degree of saturation as a results of compression the specimen during loading). The results of controlled-suction collapse tests carried out by Sun et al. (2007) [10] showed similar behavior during the over consolidated state. Beyond the preconsolidation pressure it seems to be that the gravimetric water content-suction relationship depends on the degree of saturation. If the degree of saturation is equal or higher than the degree of saturation at air-entry value (about 0.85 for 30B soil), as the case of 0, 25, 100, and 255 kPa constant suction conditions, the gravimetric water content decreased as net stress increased to keep the specimen in saturated zone. Whereas in case that the degree of saturation was moderately lower than the degree of saturation at air-entry value, as the case of 300, 400, and 450 kPa constant suction conditions, the gravimetric water content increased slightly as net stress increased till the degree of saturation reaches value around 85 % (the degree of saturation at air-entry value), then the relationship followed similar behavior of first case. The third case is when the degree of saturation was significantly lower than the degree of saturation at air-entry value, as the case of 30B-S39-Sl test under constant suction of 39000 kPa. In this case the results show that the gravimetric water content remained unchanged regardless of increasing the density due to loading. Generally, the degree of saturation decreases with increasing the suction, then increases as the net stress increases, Figure (4d).

For the initially slurry specimens under values for constant suction up to 255 kPa, the specimens remain in saturated state (except one point before loading in the 30B-S0.255-Sl test). The soil before the air-entry value, s_{aev}, is in the saturated zone and its behavior as the saturated soil. Therefore, the effective stress can be applied for void ratio and gravimetric water content, see Figure (5). In other tests, the effective stress can be applied for range of suction before air-entry value (80 kPa) only.

Figure (6) shows the results of second group of tests under constant suction condition for 30B soil: namely the initially loose state. The preconsolidation pressures are 5, 4, 100, 150, and 800 kPa under 50, 100, 4300, 10000, and 39000 kPa constant suction conditions respectively, Figure (6a). The values of the void ratios in this group before loading (points C’s) was 1.0, 1.1, 1.44, 1.05, and 1.05 under 50, 100, 4300, 10000, and 39000 kPa constant suction conditions respectively. These values can give some explanations about the relationship between the initial void ratio (initial density) and the unsaturated preconsolidation pressure. Again the increase in the preconsolidation pressure is due to the higher density before loading and hardening of soil material as suction increases. However, the yield states of 30B-S0.05-Lo and 30B-S0.1-Lo tests were achieved immediately when the suction was reduced from 5000 and 3500 kPa to 50 and 100 kPa, respectively. The results of 30B-S4.3-Lo, 30B-S10-Lo, and 30B-S39-Lo tests show that the unsaturated preconsolidation pressure increased from 100 kPa to 800 kPa as the constant suction increased from 4300 kPa to 39000 kPa. Moreover, Figure (6a) shows that the normal consolidated (yield) paths for both 30B-S10-Lo and 30B-S39-Lo tests are the same and the difference in the preconsolidation pressure is due to difference in the initial density. In other words, the results show that, for range of void ratio from 1.44 to 1.5, the unsaturated preconsolidation pressure remains almost constant when the suction was changed from 4300 kPa to 10000 kPa. The slopes of the unsaturated over consolidated path in all tests were closed to the slope of saturated over consolidated path (C_r), while the slopes of the unsaturated normal consolidated (yield) state are higher than the slope of saturated NCL. The specimen of 30B-S0.05-Lo test, as in Figure (6), had initially 5000 kPa suction (point A), and then the suction was reduced to 50 kPa under seating load (point B) which caused an increase of the gravimetric water content from 0.85 to 0.205 (point C) and reduction in void ratio from 1.56 to 1.04. While the initial suction for 30B-S0.1-Lo test, as in Figure (6), was 3500 kPa (point A), then it was reduced to 100 kPa under seating load (point B) which caused reduction in the gravimetric water content from 0.1005 to 0.190 (point C) and reduction in void ration from 1.6 to 1.06. The applied constant suction values of the other tests of this group (30B-S10-Lo, 30B-S4.3-Lo, and 30B-S39-Lo) were equaled to the initial suction. The gravimetric water content values remain almost unchanged during the yield state for high suction value (s > 4300 kPa), whereas the gravimetric water content decreased slightly in case of 50 kPa and 100 kPa constant suction conditions, Figure (6c). The results show that all the tests, during yield state had gravimetric water content-suction relationship follows the wetting path of SWCC.

Figure (7) shows the results of two different cases (slurry and loose) under constant suction condition for 100B soil. Figure (7) shows the results of initially slurry specimen under zero constant suction condition, 100B-S0-Sl. The test is a conventional one-dimensional high stress consolidation test (the specimen remains saturated during the test), in which the specimen was loaded till 24000 kPa net stress. Figure (7a) shows that, up to range of applied net stress, the 1D-NCL of the 100B soil has two different slopes. The first slope (C_{c1}) was 0.7 for net stress up to 900 kPa. Beyond this point the slope (C_{c2}) reduced to 0.37.

Figure (7) shows as well the results of initially loose specimen under 4300 kPa constant suction condition, 100B-S4.30-Lo. The initial void ratio was 2.4 and the preconsolidation pressure was about 375 kPa. The specimen had high reduction in volume after the preconsolidation pressure, then followed a path with slope higher than the slope of saturated NCL till joined the saturated NCL at 60000 kPa net stress, Figure (7a). The gravimetric water content values slightly changed (decreased) during the yield state, Figure (7c). The degree of saturation increased due to compression till reaching the full saturation state at 12000 kPa net stress (S_r = 90 % at 6000 kPa net stress when the curve joined the saturated NCL), Figure (7d).

The observed behavior, the slope of the unsaturated NCL is higher than the slope of saturated NCL, is similar to the results of ([11]; [12]; [13]; [14]; [15]; [16]; [17]; [18]; [19]; [20]; [21]; [22]; and [23]). This behavior confirms the assumption of some unsaturated soil models (e. g. [12]; [14]; [20]; and [24]), while it disagrees with other unsaturated soil models, where they are assumed that the slope of the unsaturated NCL is lower than the slope of saturated NCL (e. g. [25] , [26])

Agus (2005) [6] pointed out that the apparent pre-consolidation pressure of the 50 % bentonite-sand mixture specimens generally increases with increasing suction indicating that the material hardened as suction increases. This behavior is generally similar to the behavior of tested bentonite-sand mixtures (30B and 100B) in this study. Pham and Fredlund (2005) [27] presented results showing that during the compression process at constant soil suction for an unsaturated soil, the degree of the saturation always increases with an increment of net vertical stress. Jotisankasa (2005) [21] cited that the contours of constant suction NCLs for suctions between 10 and 100 kPa appear to be slightly curved and converge towards the fully saturated (zero suction) NCL at high vertical stresses. But the NCLs for higher suction showed straight line behavior. It is expected that the NCLs for higher suction would also converge toward the fully saturated NCL if the samples are loaded to high enough net stresses. Moreover, his results show that all the contours of constant suction NCLs have a slope larger than the saturated NCL. The behavior of soil in the work of [21] is very close to the observed behavior of tested bentonite-sand mixtures in this study.

CONCLUSIONS

Considering the results of experimental program for the specific range of densities, net stresses, and suctions used in study, the following key observations can be derived:

- The suction stress has isotropic effect.
- The preconsolidation stress increases as the applied suction increases.
- The position and the slope of NCL's depend on both net stress and suction.
- The NCL's either, for low suction value, has void ratio lower than the saturated NCL (associated with slope lower than the saturated NCL), or the NCL has void ratio higher than the saturated NCL (associated with slope higher than the saturated NCL) for higher suction value.

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Table (1) The properties of bentonite and sand used.

Soil used	Bentonite	Sand
Gs	2.75	2.65
L.L.%	89.1	-
P.L. %	35.9	-
S.L. %	14	-
Total SSA (m2/g)	400	0.25

Table (2) Initial conditions of specimens for the constant suction test.

Nr	Test name	soil/ Initial state	constant suction, (MPa)	Initial void ratio	Initial dry density, (gm/cm^3)	Initial water content, (w)	Initial degree of saturation (S_r)	Initial total suction (MPa)
1	30B-S0-Sl	30B/Sl	0	0.89	1.42	0.33	1.00	0
2	30B-S0.05-Sl	30B/Sl	0.05	1.08	1.29	0.355	0.94	0
3	30B-S0.1-Sl	30B/Sl	0.10	1.02	1.33	0.375	0.994	0
4	30B-S0.255-Sl	30B/Sl	0.225	0.98	1.36	0.34	0.94	0
5	30B-S0.3-Sl	30B/Sl	0.3	0.98	1.36	0.344	0.943	0
6	30B-S0.4-Sl	30B/Sl	0.4	0.914	1.41	0.35	1.00	0
7	30B-S0.45-Sl	30B/Sl	0.45	1.03	1.31	0.365	0.952	0
8	30B-S39-Sl	30B/Sl	39	1.00	1.32	0.375	1.00	0
9	30B-S0.05-Lo	30B/Lo	0.05	1.65	1.04	0.085	0.14	5

10	30B-S0.1-Lo1	30B/Lo	0.1	1.83	0.95	0.100	0.147	3.5
11	30B-S4.3-Lo	30B/Lo	4.3	1.44	1.11	0.075	0.14	4.3
12	30B-S10-Lo	30B/Lo	10	1.50	1.08	0.07	0.126	10
13	30B-S39-Lo	30B/Lo	39	1.05	1.34	0.053	0.135	39
14	100B-S0-Sl	100B/Sl	0	2.71	0.74	0.994	1.00	0
15	100B-S4.3-Lo	100B/Lo	4.3	2.4	0.81	0.243	0.28	4.3

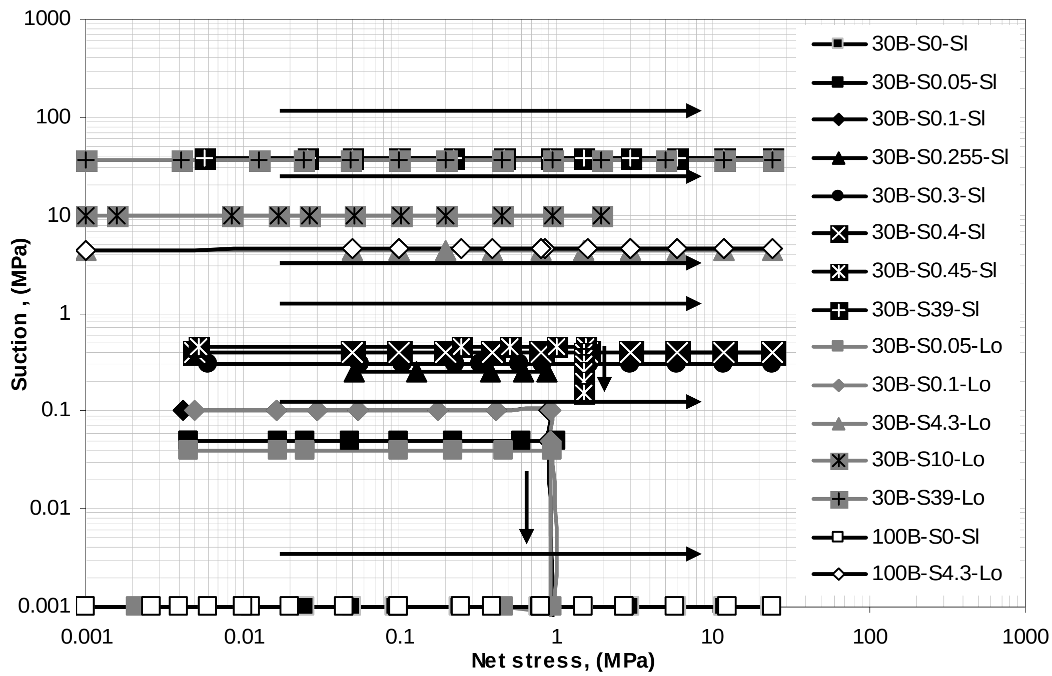
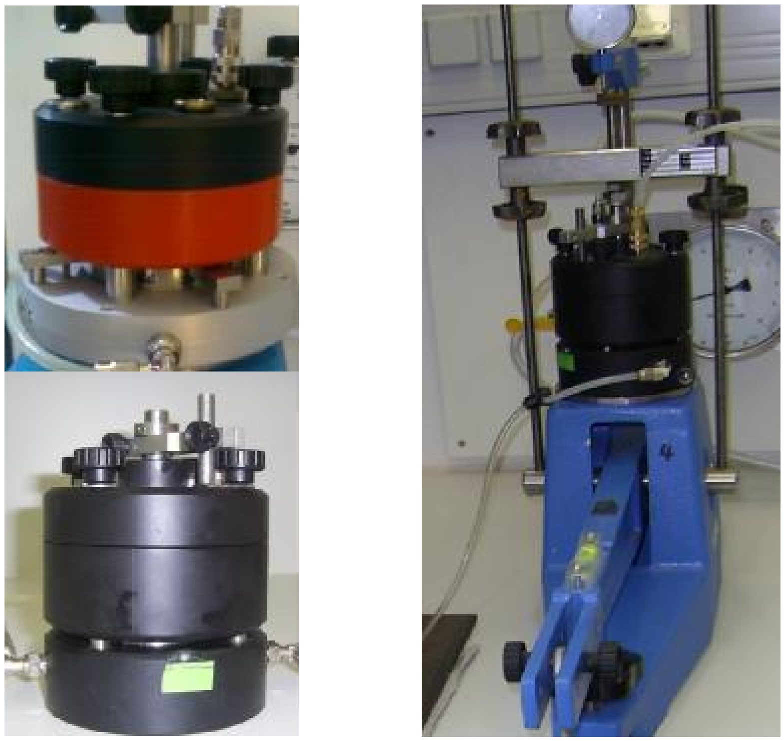


Figure (1) Stress paths of constant suction tests for 30B soil.



(a) **(b)**

Figure (2) Modified controlled-suction oedometer cells: (a) Red and black cells (b) appling net (vertical) stress.

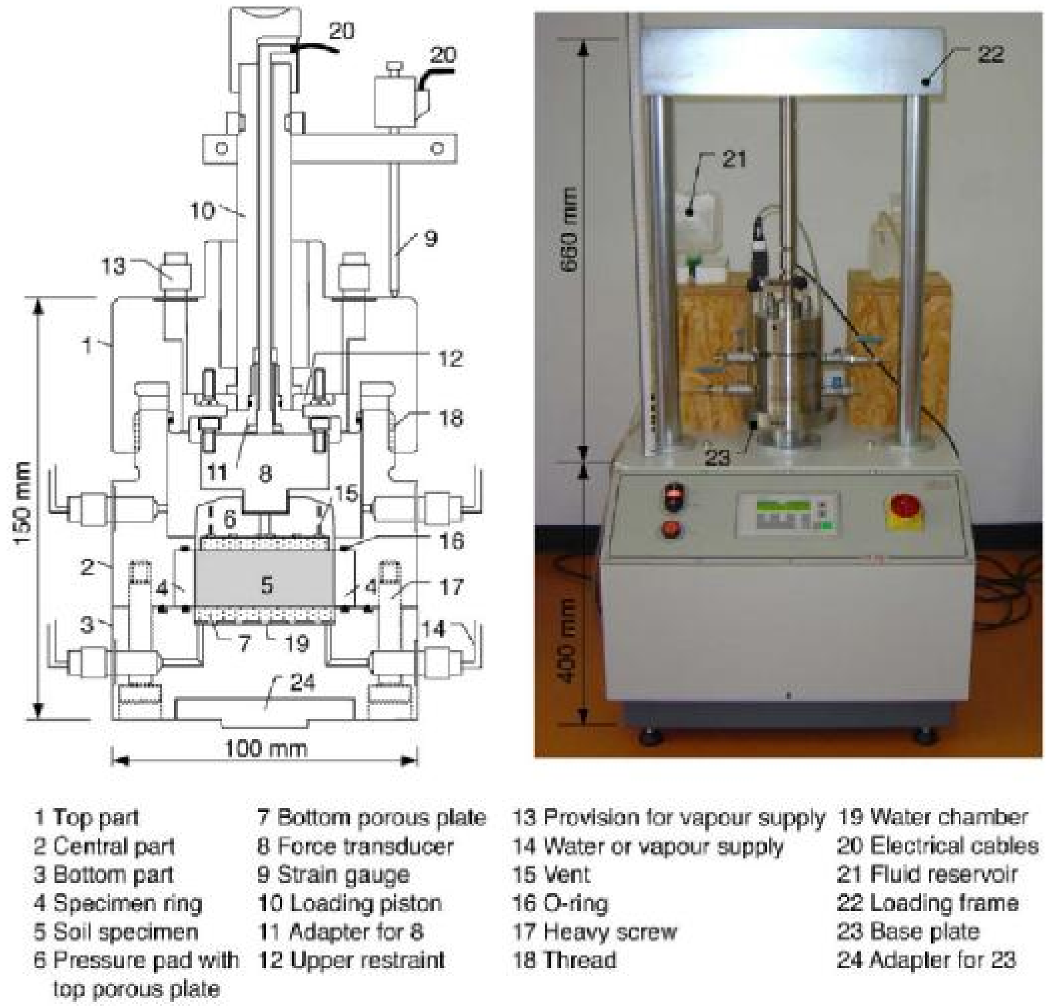


Figure (3) New HSC with sketch of the cell (left), and the test set up (right), (Baille et al., and 2010).

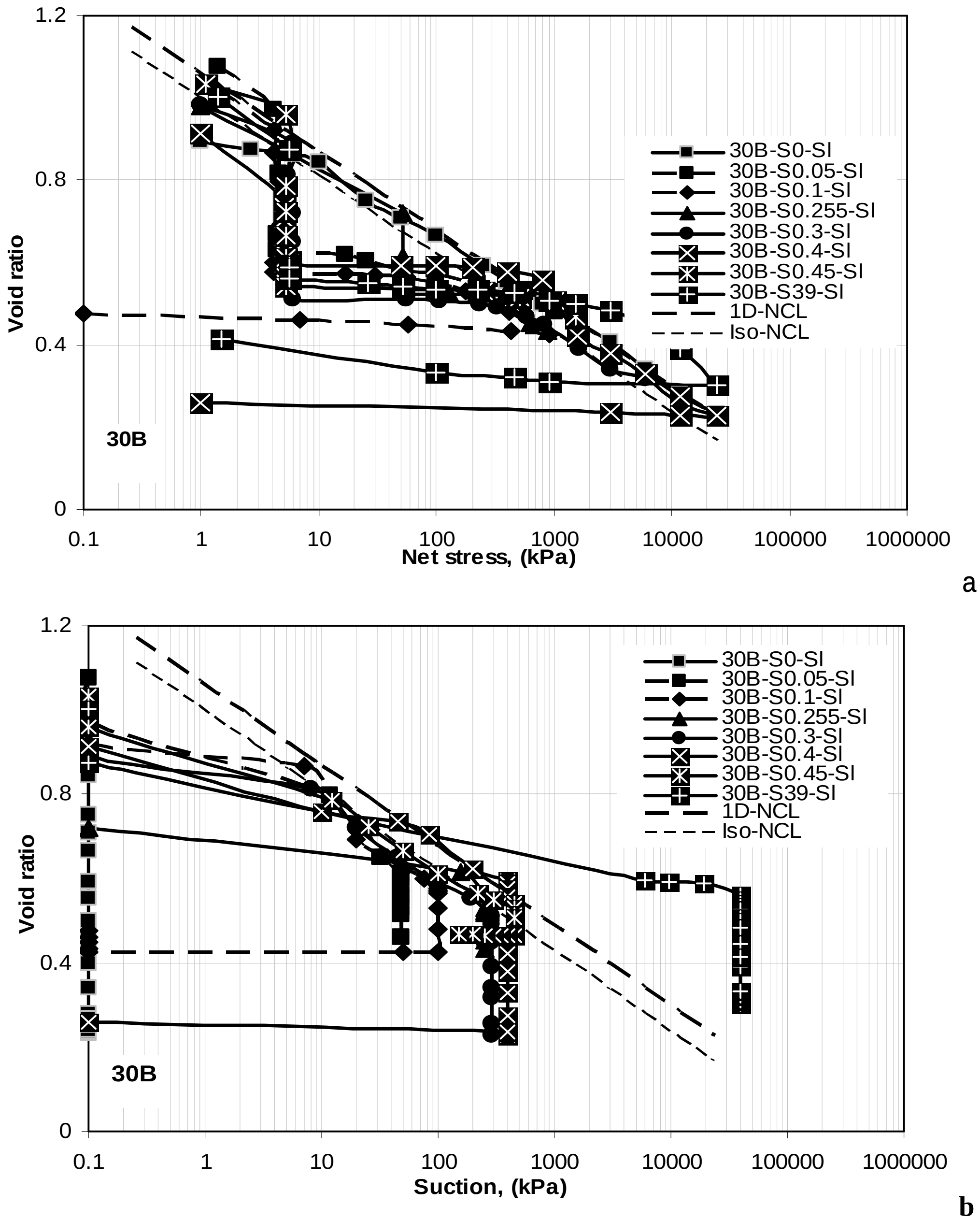
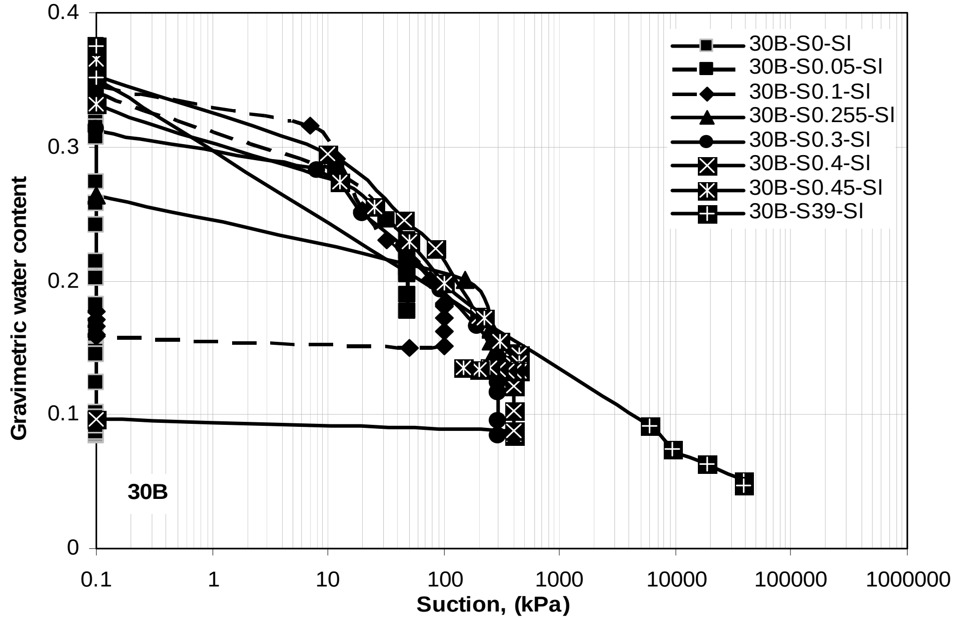
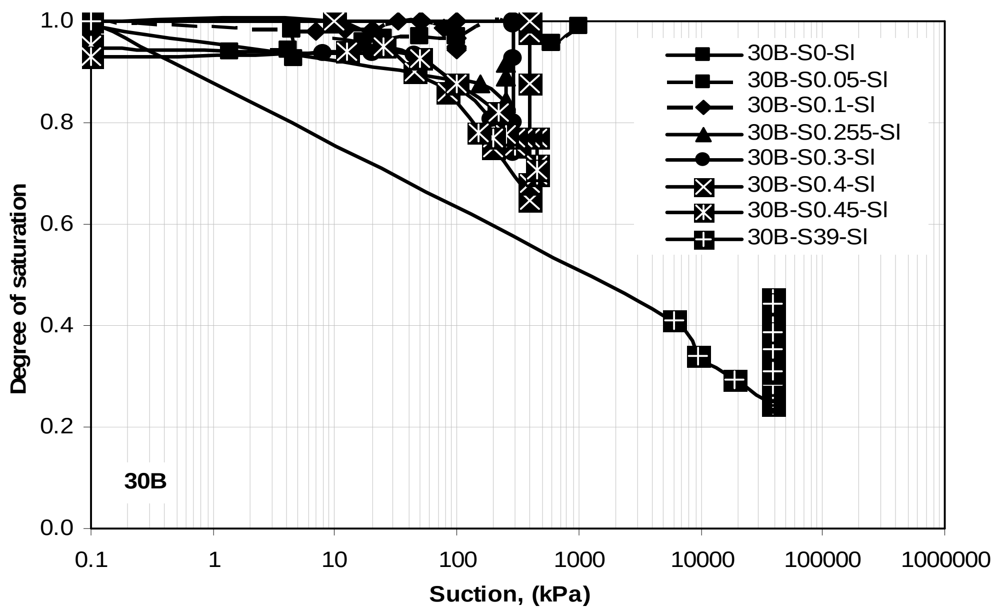


Figure (4) Void ratio, gravimetric water content, and degree of saturation results of all constant suction condition for initially slurry 30B soil.

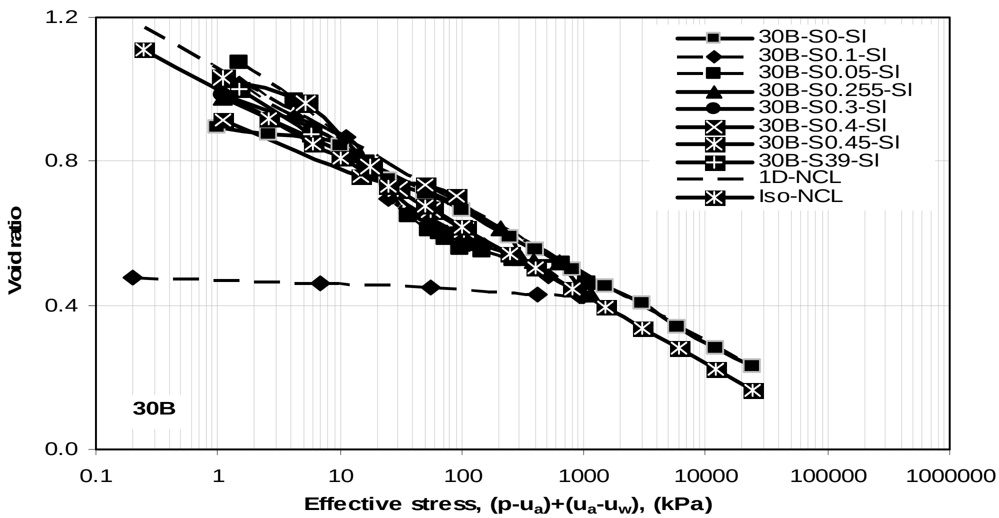


c

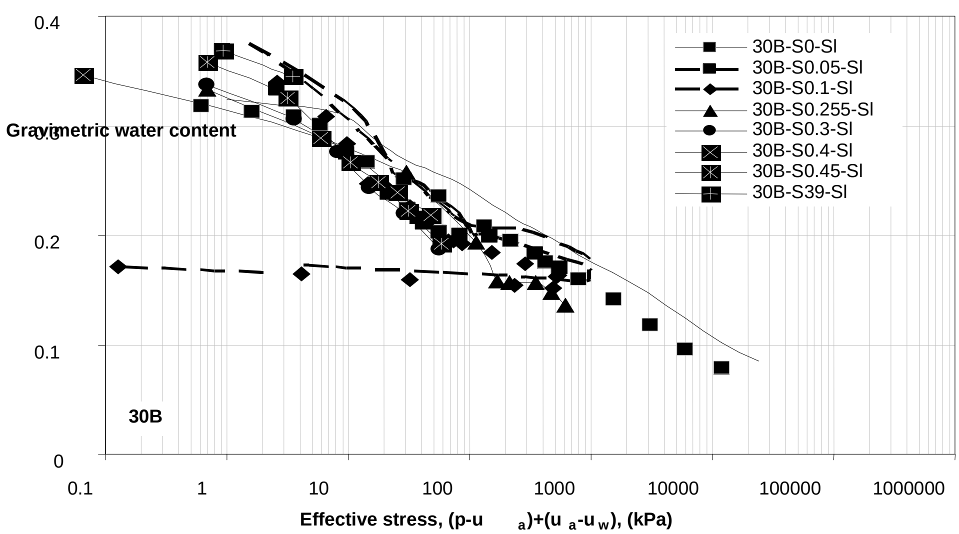


d

Figure (4) Continued.

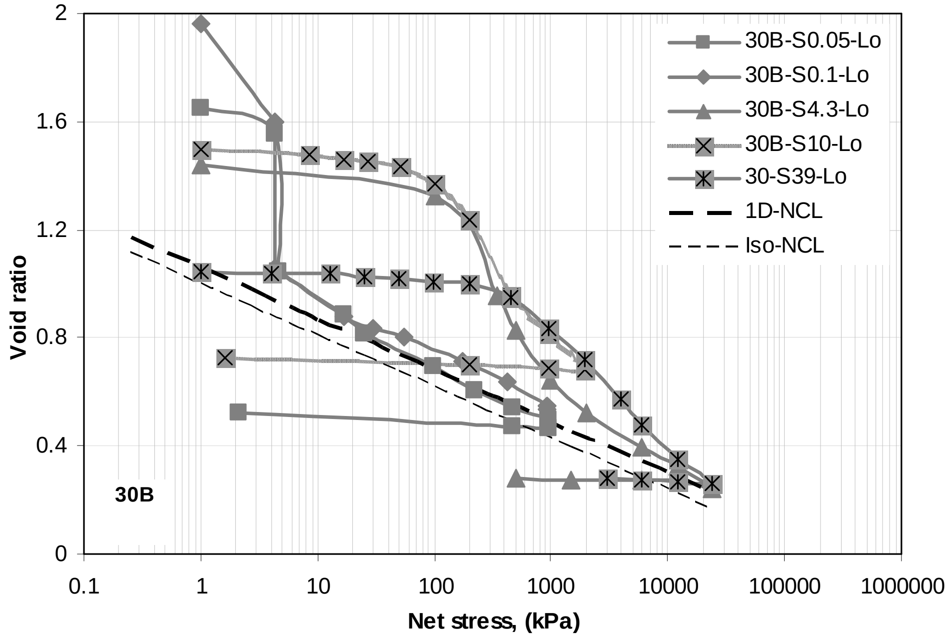


a

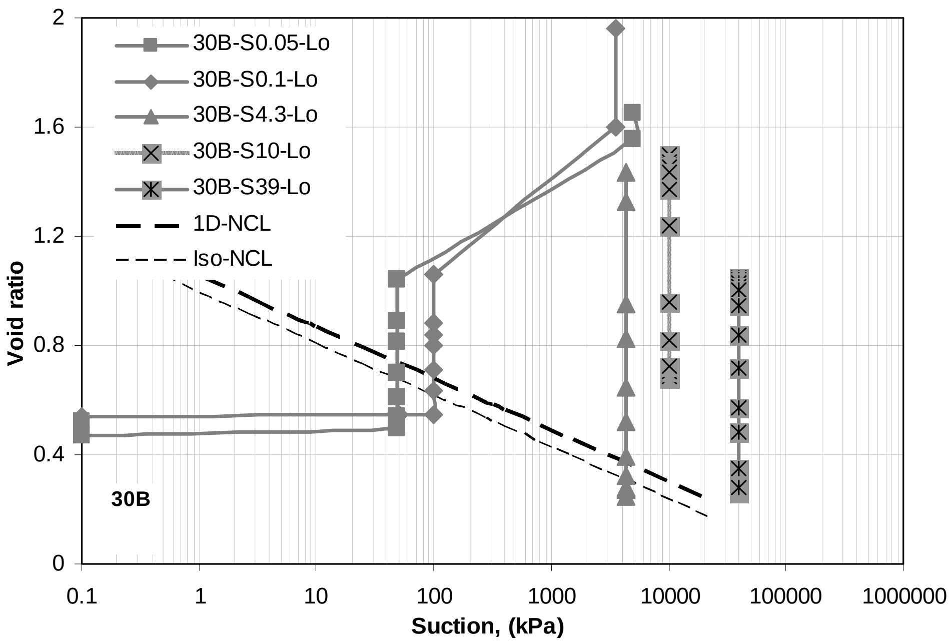


b

Figure (5) Void ratio and gravimetric water content verses effective stress Relationships for saturation zone of all constant suction condition for initially slurry 30B soil.

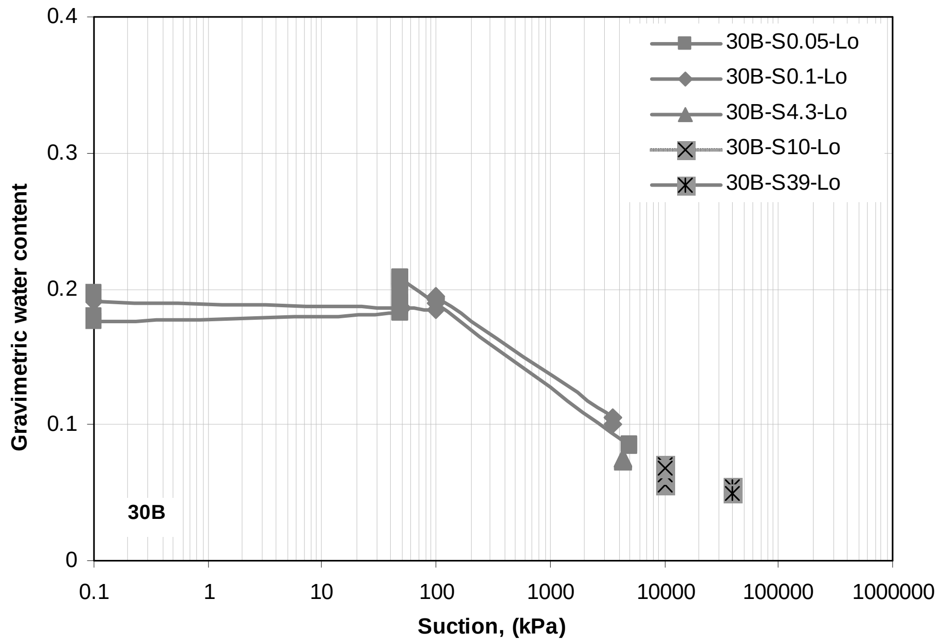


a



b

Figure (6) Void ratio, gravimetric water content, and degree of saturation results of all constant suction condition for initially loose 30B soil.



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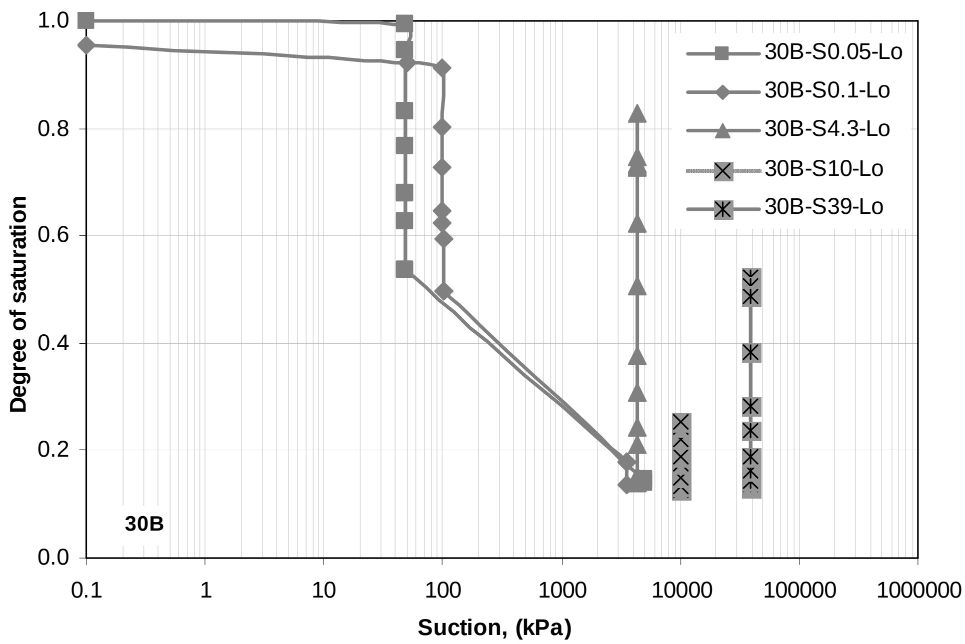
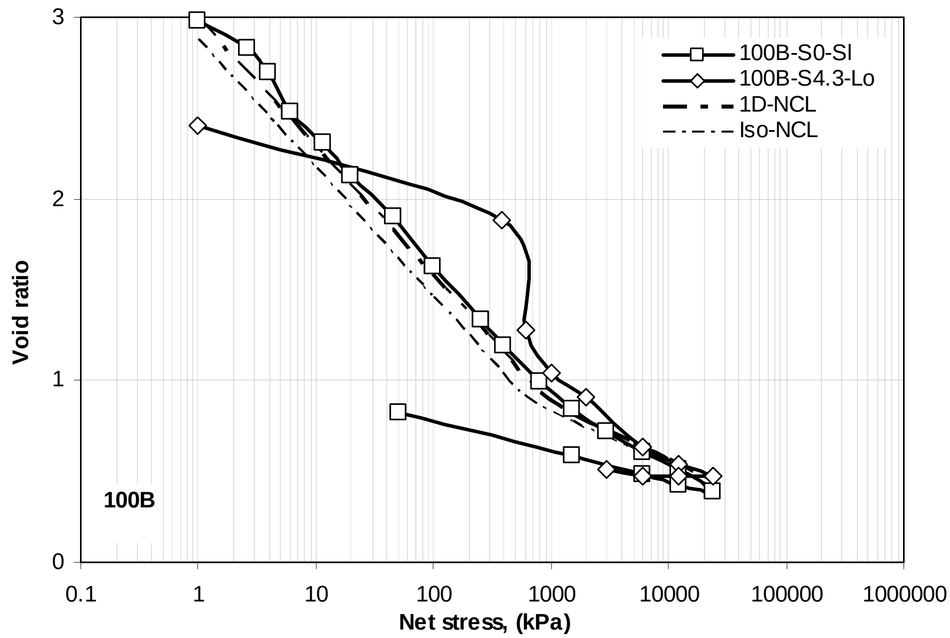
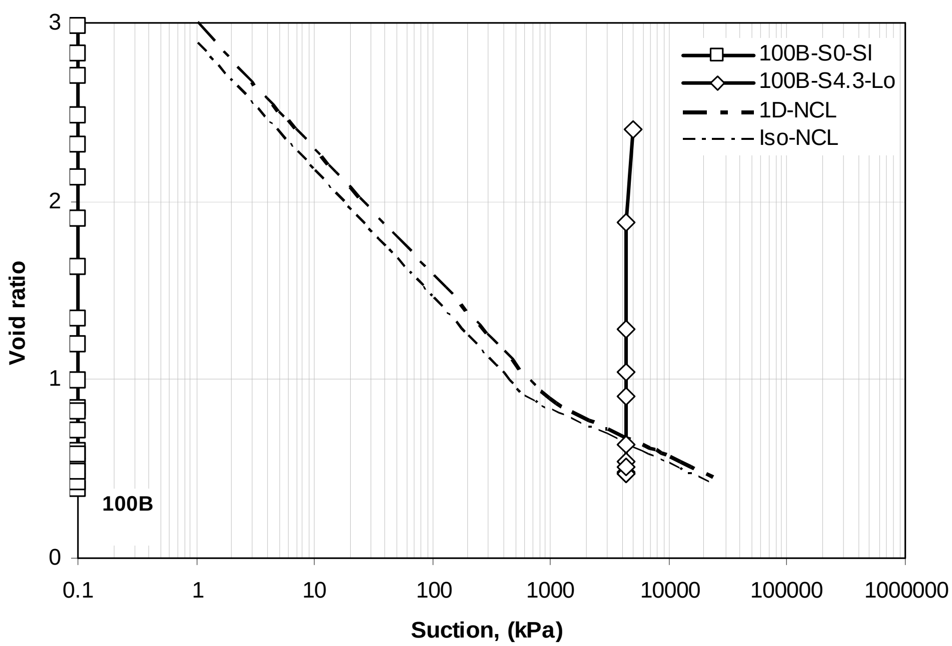


d

Figure (6) Continued.

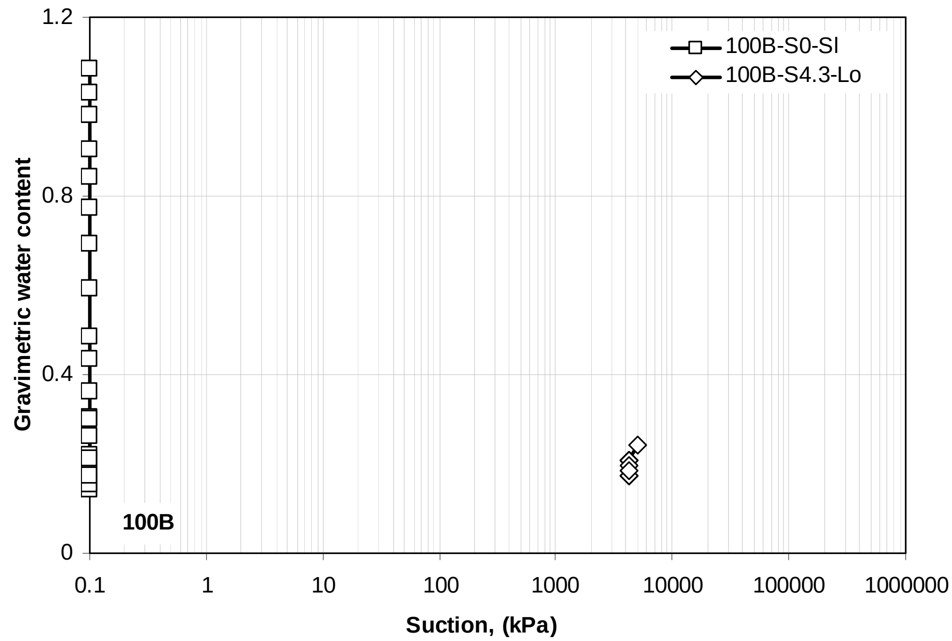


a

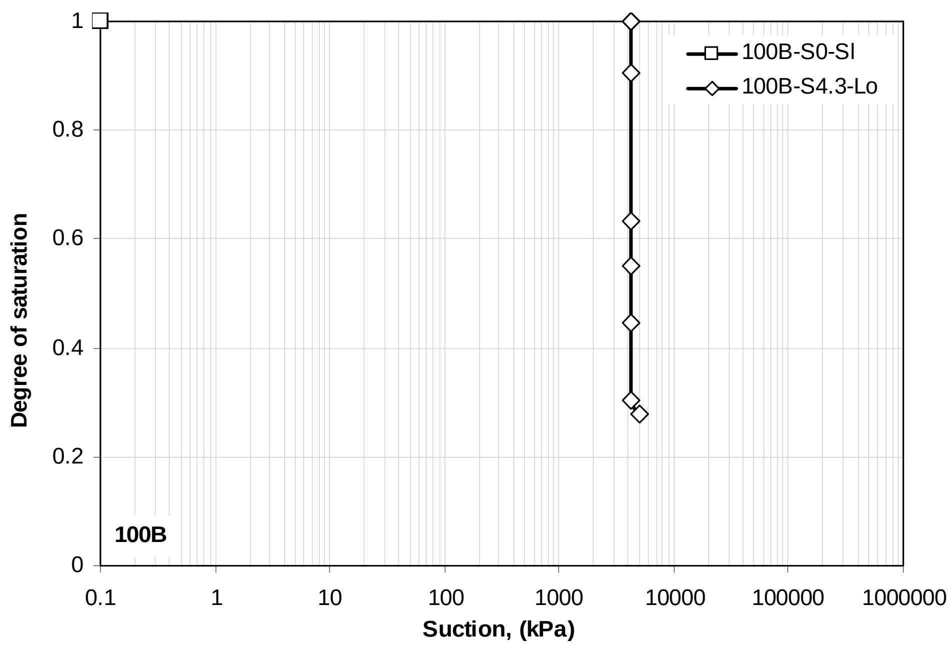


b

Figure (7) Void ratio, gravimetric water content, and degree of saturation results for both constant suction condition for initially slurry and loose 100B soil.



c



d

Figure (7) Continued.