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SOIL-WATER RETENTION AND DRAINAGE DURING SHEAR OF AN UNSATURATED GRANULAR MATERIAL

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Abstract

The soil-water characteristic curve reveals that a first set of specimens of dense crushed sand and gravel with 8.9% fine particles content proves unable to maintain a saturated state under a positive matric suction. Capillary physics explains how this could result from the presence of millimetre size pores and why certain soils might display a null air-entry value. Unsaturated drained triaxial compression tests performed on a second set of samples confirm a relationship of the degree of saturation with the void ratio and matric suction while shearing. This defines a soil-water characteristic surface that is in turn used to analyze why loading induces the observed continuous outflow of water. Contrary to intuition, the results of this study show how the uninterrupted drainage during both contraction and dilation phase appears to remain compatible to the soil-water characteristic surface model. Furthermore, shearing of unsaturated materials that contract and then dilates creates a transitional wetting followed by drying cycle.

Key words

Soil-water characteristic surface, air-entry value, unsaturated soil, drained triaxial shear

1 Introduction

It stands established that drained shearing of dense saturated granular soils initially induces volumetric contraction and outflow of water. Further loading leads to volume expansion while water inflows into the sample. Khoury and Miller (2012) and Rahardjo et al. (2004), among others, report data where this one-to-one relationship between water flow and volume change no longer holds during drained shearing in an unsaturated state. They rather observe a continuous expulsion of water, even throughout the dilation phase. It appears that this phenomenon remains unexplained when writing this paper.

Ke et al. (2013) showed for three clean sands that at a set suction, a smaller void ratio yields a higher degree of saturation. Gallipoli et al. (2003) point out for their part that in a deformable soil, variations in the void ratio alters the size of the voids and of connecting pathways. This will necessarily lead to a change in the water retention curve. Using data from isotropic consolidations at constant matric suctions on a compacted Speswhite Kaolin, they confirmed that the degree of saturation rises as void ratio decreases. They also corroborated this in a drained unsaturated triaxial test at constant matric suction where the decreasing volume produced by the application of a stress difference q under constant net stress also conducted to an increasing degree of saturation. During both these types of volume contraction, the degree of saturation thus rose as the void ratio decreased. On this basis, they developed a model for a soil-water characteristic surface. It involves matric suction, the degree of saturation (which characterizes the soil's capillary capacity to partially fill voids with water) and the void ratio (that relates to the relative void size and interconnections). As for water drainage during loading, it isn't addressed.

This study aims to ascertain why drained triaxial shear of an unsaturated dense granular soil induces water outflow throughout both contraction and dilation phases. It evaluates the soil-water characteristic curve (SWCC) and examines the air-entry value of coarse materials for a first set of specimens that display large voids. It proceeds with reporting results obtained on a second set (exhibiting no macro pores) from triaxial compression CD tests. These are performed after a desorption stage alone and after a cycle of desorption followed by sorption. Soil-water retention during shear is investigated and its link to the void ratio. It finally pays attention to the continuous water outflow throughout loading and changes in the degree of saturation (soil-water retention) and how this relates to matric suction and void ratio.

2 Methods

The studied crushed sand and gravel contains 8.9% of non-plastic fine particles. This well-graded soil gives coefficients of uniformity and curvature of 35 and 5.9. The triaxial shearing method in unsaturated state used a modified Bishop and Wesley triaxial cell such as described by Fredlund and Rahardjo (1993). Specimens manufacturing proceeded by a successive static compaction of five (5) 20 mm layers in a 50 mm diameter mould to attain the standard optimum proctor of 2100 kg/m3 in dry density at 7% water content (Figure b). These then sit on a 300 kPa HAEV (High Air-Entry Value) porous stone (saturated in advance) embedded in a pedestal and topped by a coarse-grained porous stone. Saturation starts by a slow water inflow by the base under a partial vacuum applied at the top. Valve closure follows when water exits into the upper drainage line. Successively increasing by small increments the back and cell pressures up to 500 kPa (the latter always higher by 10 kPa) ends this step. A Skempton coefficient (B) of 0.97 served to confirm saturation. The action of an isotropic net confinement stress then consolidates the saturated soil specimen. This is judged complete when the pore pressure attains the back pressure.

Desorption begins by applying air pressure (u_a) at the top end equal to the water back pressure (u_w) from the base. Subsequently decreasing the latter creates a matric suction (u_a-u_w) that dries the sample by water drainage through the base. The desorption-sorption cycle starts by desorption under a matric suction of 295 kPa. Following this, increasing the water pressure to an aimed value lowers the matric suction and induces water flow back into the specimen. During this desaturation operation called the equilibrium phase, the isotropic confinement stress remains unchanged. This axis-translation technique makes it possible to set the matric suction to a target value while maintaining the net confinement stress (σ_3 - u_a) constant under positive air and water pressures. Axial loading then proceeds at a constant strain rate of 0.01 mm/min up to 15% of total axial strain. A constant matric suction ($u_a - u_w$) and constant net confining stress ($\sigma_3 - u_a$) throughout loading characterizes the unsaturated CD triaxial test. Under a drainage condition by the base (water) and top end (air) of the specimen, excess pore water and pore air pressures created by shearing both dissipate during testing.

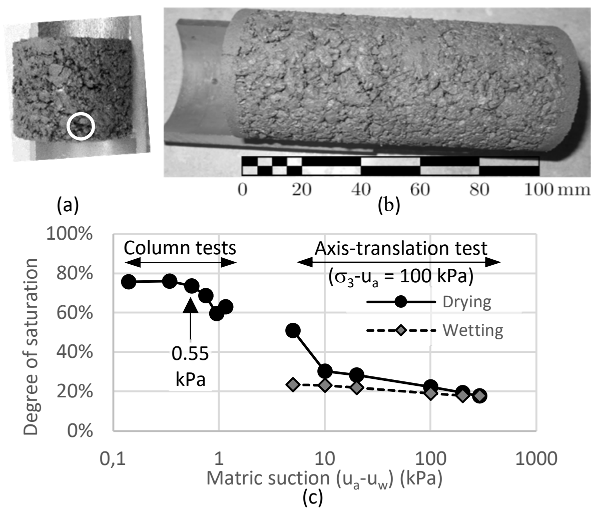

Figure 1. Specimens for (a) measurement of soil-water retention (circled void at left has an approximate width of 6 mm) and (b) unsaturated triaxial shear; (c) Soil-water characteristic curve as determined by column tests ($\sigma_3 - u_a$ = 0 kPa) and by axis-translation technique in the triaxial cell (σ_3 - u_a = 100 kPa).

Measurements of the SWCC at matric suctions above 5 kPa proceeded in the modified triaxial apparatus by using the axis-translation technique under 100 kPa of net isotropic confinement pressure ($\sigma_3 - u_a$). The 50 mm diameter specimen had a reduced height of 40 mm (Figure a). This low height minimizes time to attain a constant water content. The equilibrium of the matric suction in the specimen is assumed to be achieved when the volume of water drained from the specimen becomes asymptotic over time. The closure of the drainage valve and the subsequent evaluation of the water pressure proved to stabilize at the targeted matric suction. This validated this method for determining the end of drainage.

Measurements for lower matric suctions used column tests. Material static compaction proceeded in a steel tube by a succession of 20 mm layers up to a total height of 120 mm. This permitted to apply precise matric suctions between 0.10 kPa and 1.1 kPa. Drying tests start by saturating the column under vacuum in an air- and water-tight cell and a slow water inflow from the base. Once saturation confirmed by reaching the targeted total mass, cell and specimen were then let to drain by the base soaking in water. Columns tests were extended up to 47 days to stabilize within 0.1 g of total setup mass, ensuring an error below 0.2% in degree of saturation.

3 Results

The following first presents the soil-water characteristic curve before proceeding with the results of the triaxial CD tests.

3.1 Measurements and interpretation of the soil-water characteristic curve

Desorption column tests immediately reveal an unsaturated state at a matric suction value of 0.14 kPa (Figure c). This 14 mm total water head corresponds to one of the lowest achievable matric suctions by this method that allows a reliable measurement of water content on a representative volume. Generally, conceiving a representative volume of material necessitates a specimen thickness of at least 20 mm. Since 0 kPa equates to the smallest attainable matric suction at the base, the top end develops 0.196 kPa. This gives a lower boundary of 0.098 kPa for the average matric suction.

The studied soil maintains approximately 74% saturation for the two subsequent measurements (Figure c). It then dries up abruptly beyond matric suctions of 0.55 kPa at a desaturation gradient of 25.3%/kPa. It falls to a degree of saturation of 61.3% at a matric suction of 1.05 kPa.

Attaining higher matric suctions in column tests requires higher specimens that increase their duration exponentially. A change of method therefore becomes necessary. This study used the axis-translation technique for this purpose. However, these tests were carried out under a net confinement stress which increases the air-entry value of unsaturated soils (Vanapalli, 2009). These latter measurements will therefore be translated to the right compared to those taken from column tests. This may explain a certain discontinuity in the data of the two methods as presented in Figure c.

The axis-translation test under a net confinement stress ($\sigma_3 - u_a$) of 100 kPa shows that the degree of saturation continues to drop abruptly to a residual value of about 30% at a matric suction of approximately 10 kPa (or less). The degree of saturation then decreases at a low rate on a logarithmic scale to attain 17.8% at a matric suction of 290 kPa. During subsequent sorption (wetting), the material absorbs water at an even lower gradient (Figure c) up to a water-entry value with a degree of saturation in the order of 23.5% and a matric suction below 5 kPa (500 mm of water head).

Between matric suctions of 0.14 kPa to 0.55 kPa, it is interesting to observe that water content in desorption columns rest on a sill below 100% saturation. In other words, not all the pores of the tested specimen seem capable of maintaining themselves in the saturated state. Although no one appears to report this observation, calculations based on water content data published by Zhao and Zhang (2014) give a degree of saturation sill value of 92%. Their material (90% coarse particles) displayed a double porosity. It contained 10% non-plastic fine particles, which compares to the 8.9% of this study.

Rigorously speaking, the true height of capillary rise depends on the Young-Laplace equation which defines matric suction (or Laplace pressure) u_a - u_w in function of the air-water interface geometry by:

$$u_a - u_w = T_s\left(\frac{1}{r_1} + \frac{1}{r_2}\right) \tag{1}$$

In this equation, r_1 and r_2 define the principal radii of curvature at a point on the air-water interface while T_s corresponds to the surface tension (72.75 mN/m at 20 °C). By assuming it forms the surface of a spherical sector with a solid-liquid contact angle θ, the radius R of a capillary tube will correspond to the contractile skin's principal radii of curvature. Since the air pressure u_a applies on the air-water interface on both the inner side and outer side of a capillary tube, (1) becomes:

$$h \cong \frac{2T_S \cos\theta}{\gamma_w R} \tag{2}$$

Where γ_w corresponds to the unit weight of water. This latter expression, known as Jurin's law, defines the height of ascent h in a capillary tube as a function of its inner radius R. According to this law and a null contact angle, a capillary ascent of 5.4 mm should be observed in a tube of the same diameter. If this law applies to soils, only voids below this size may maintain saturation by capillarity. Jurin's equation, however, has its limits of appropriateness. Moving away from the wall of a large diameter tube, gravity takes over surface tension, and the contractile skin flattens. In this case, the earlier assumed spherical contractile skin overvalues true capillary ascent. The distance where gravity (the weight of the water column above the free surface) equals the Laplace pressure defines the capillary length l_{ca} (de Gennes et al., 2004). Jurin's law doesn't overestimate the height of the capillary rise when the radius of the tube falls much smaller than the capillary length ($R \ll l_{ca} = \sqrt{T_s/\gamma_w}$). A temperature of 20 °C gives a capillary length of 2.7 mm, meaning that the earlier discussed 5.4 mm diameter tube would yield a lower capillary ascent. It should rather be in the order of 4.7 mm according to the Prokhorov (1996) correction. Hence, a tube gives a height of capillary ascent equal to its diameter when the latter is of 5.1 mm. Assuming a soil has the same rise as a capillary tube, capillarity may maintain saturation of a 5.1 mm high soil column only if its maximum pore size falls smaller than 5.1 mm. This would give such a soil an air-entry value of 0.05 kPa. However, this defines an unattainable upper boundary limit. This maximum pore size should turn out much smaller, since the soil pore network bears no resemblance to tubes of circular cross-section. Lourenço et al. (2012) also reports that the shape of the contractile skin of water in soils adopts much more complex configurations than the concave and regular surface observed in a capillary tube. Hence, the relationship between the contractile skin's average radius of curvature and the pore size of a soil certainly differs from that with the diameter of a capillary tube. As a result, the maximum pore size capable of maintaining a state where water fully occupies it through capillarity would prove somewhat smaller than the diameter of a tube that yields a capillary rise equal to its height.

As equation (2) indicates, capillary rise also depends on the solid-liquid contact angle. The latter extends in a wetting sand from 60° to 80° and 30° to 80° for drying (Lu & Likos, 2004). In small tubes where Jurin's law applies (D < 2.5 mm), this reduces capillary rise by a factor of 0.17 to 0.87 for a contact angle of 80° to 30° respectively. To satisfy minimum volume representativeness, this study used column test of piled 20 mm segments in thickness to measure their water content and degree of saturation in function of the matric suction. For the subsample at the bottom of the column, assuming a 30° contact angle and that Jurin's equation applies, water may, at best, rise to the 10 mm mid-height and the 20 mm full height if pore sizes respectively correspond to 2.6 mm and 1.3 mm.

For the tested soil specimens, it appears that the matric suction of 0.55 kPa shown in Figure c draws a limit, where larger interconnected pores cannot maintain a greater degree of saturation by capillarity (they yield lesser capillary rise than their size). With the supposed 30° contact angle, Jurin's law gives for a matric suction of 0.55 kPa a diameter of 0.46 mm. Interestingly, more rigorous capillary pore size distribution computations based on a numerical integration procedure described by Lu and Likos (2004) produces a comparable result of 0.29 mm in size. Jurin's equation can thus serve to define a pore size

upper boundary linked to the air-entry value. For the studied soil, this upper boundary pore size corresponds to the air-entry value of its finer void matrix.
Visual inspection of specimens shows on the surface the presence of smaller millimetre size voids that interconnect larger voids ranging up to the order of 6 mm in width (Figure a and b). Arching of coarser particles against the steel mould throughout sample preparation seems the cause of the latter. According to the preceding discussion, the pore network appears likely to permit air penetration from top to bottom during drying. The resulting drainage would explain why the tested specimens cannot retain water at degrees of saturation higher than 74% (Figure c). This doesn't necessarily mean that they display a null air-entry value. Even 6 mm pore sizes should yield some capillary rise. Unfortunately, practical considerations impose a minimum sample thickness. To produce a soil-water characteristic curve requires to measure water volume (or mass) within a given total volume at a set matric suction. Exerting a matric suction at the level of the tested specimens' low air-entry value would require to prepare a sample with a height in the order of one to two millimetres. Considering the presence of particle sizes up to 6.3 mm in the material under study, this clearly proves unfeasible.

Hence, in the case of drying an initially saturated soil displaying a pore network unable to maintain its water content by capillarity, the air-entry value would mark a discontinuity in water content. The resulting SWCC should follow a step function, jumping from a saturated state to a degree of saturation somewhat below 100% when the matric suction crosses the air-entry value. This compares to the situation of the 100% degree of saturation of a set point somewhere under the contractile skin in a capillary tube. If the water level falls, the degree of saturation remains at 100% until the contractile skin attains the set point. It will then suddenly jump like a step function to a null value with a further infinitesimal drop of the water level.

The preceding arguments lead to postulate that certain soils may show a null air-entry value and a SWCC that follows a step function. In these soils, there exists an interconnection of "very" large pores characterized by very limited capacity to lift water by capillarity. This may turn out the case of clean uniform materials with particles of coarse gravel size or greater such as railroad ballast or rockfill. Whatever the air-entry value, an SWCC exhibiting a step function should have interesting repercussions on the hydraulic conductivity function. Since the air-entry value links to no single water content value, the same should be observed for the hydraulic conductivity when formulated as a function of the matric suction. For water flow computations, it should be possible to circumvent this difficulty by expressing it as a function of the degree of saturation, where there would exist a unique correspondence. Confirming these hypotheses needs further research. If they were to prove true, interesting consequences should result for problems such as the modelling of water flow in capillary barriers when matric suction reaches the air-entry value of the coarser layer.

3.2 Saturated triaxial tests

Three CD saturated triaxial tests at effective confinements of 25 kPa, 100 kPa and 200 kPa were performed to determine mechanical parameters such as the failure criterion and the volume change throughout shearing of the studied soil. In general, the material behaves under shearing as a dense granular soil and its failure envelope from the three CD saturated tests reveals zero effective cohesion (as with any granular material) and an effective friction angle of 43.1°.

3.3 Unsaturated CD triaxial tests in desorption

Shearing behaviour in the unsaturated state on the drying path was investigated through 15 CD triaxial tests. These were performed for matric suctions ranging from 5 kPa to 290 kPa under net confinements of 100, 150, 200 and 250 kPa. Among them, five (5) unsaturated triaxial loadings were carried out at a constant net confinement of 100 kPa under matric suctions of 5, 50, 100, 200 and 290 kPa (Figure presents the first three tests). Chiasson and Tamégnon (2023) used these same data to evaluate the hysteresis of the mechanical behaviour in drained loading performed after drying alone and after a drying and wetting cycle.

Shearing leads to total volume adjustments with initial contraction followed by expansion (Figure b). Water volume drains continuously during tests performed after initial drying (curves identified by Dxxx in Figure c), even through the dilation phase (except for the 100 kPa matric suction test which absorbs water beyond 4.5% axial strain). These variations to total and water volumes result by consequence into changes in the degree of saturation.

The degree of saturation during loading rises slightly for the first 0.5% to 1% axial strain (Figure d), meaning that the volume of voids in the unsaturated sample decreases faster than the volume of water retained in the pores. This constitutes an almost purely elastic stage where the plastic strain of the specimen remains low (little particle rearrangement). Beyond 0.5 to 1% of axial strain, the degree of saturation declines as axial strain increases. Above 7% axial strain, the rate of change in the degree of saturation dissipates, a sign that the material progresses towards a state of equilibrium even if it continues to deform (grains persist to move relatively to each other). At this stage, the rate of volume change also tends towards zero (Figure b).

Total and water volume changes plot a path in the degree of saturation to matric suction graph (Figure). The SWCC first heads slightly upwards then descends, passing through the value reached at peak shear strength and pursuing asymptotically towards a minimum. Loading thus creates a set of characteristic curves. It is worthwhile noting that a drained test at a constant matric suction doesn't imply a constant degree of saturation during shear. Forgetting this fact often occurs.

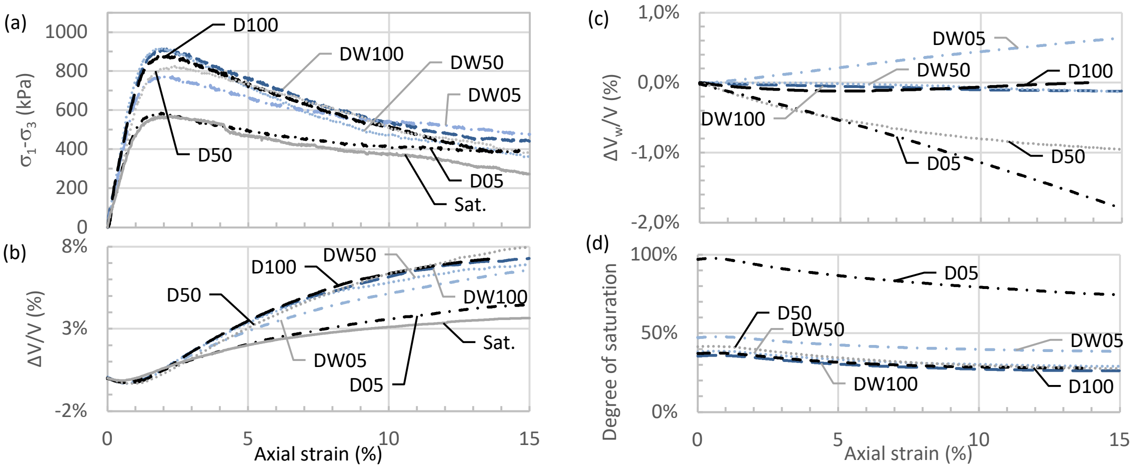

Figure 2. Saturated (σ'_3 = 100 kPa) and unsaturated on the drying path (σ_3 -u_a = 100 kPa) CD triaxial tests: (a) principal stress difference; (b) volumetric strain; (c) change in volumetric water content; (d) degree of saturation.

3.3 Unsaturated CD triaxial tests after a desorption-sorption path

Mechanical properties of the studied soil were determined on the desorption-sorption path using three (3) triaxial CD tests at matric suctions of 5, 50 and 100 kPa and submitted to a constant net confinement stress of 100 kPa. This confinement, identical to that employed on the desorption path, allows a comparative investigation of the effect of wetting (sorption). The desorption-sorption path follows in order: saturation, consolidation under confinement stress, drying under a matric suction of 295 kPa and wetting by decreasing the matric suction to the target value.

Following the desorption-sorption path, the studied soil shares several behaviours observed in saturated and unsaturated desorption loadings (Figure). As in the case of unsaturated triaxial tests on the drying path, the material after sorption shows a similar evolution in the degree of saturation during shearing. However, the degrees of saturation at failure fall lower than those measured on the drying path (Figure d). The primary distinction lies in a minute change in volumetric water content comparatively to that of the desorption path tests (Figure c). The change in the degree of saturation proves therefore mainly due

to total volume change.
Decreasing the applied matric suction on the desorption-sorption path gradually tends to shift from water discharge to absorption. For sorption at the higher 100 kPa matric suction, loading leads to a continuous, although very low, expulsion of water. This outflow declines when lowering the set matric suction and turns out close to null for a wetting matric suction of 50 kPa at axial strains of less than 4.5%. It even reverses into water absorption when shearing after initially wetting down to the lowest tested 5 kPa matric suction (DW05 in Figure c).

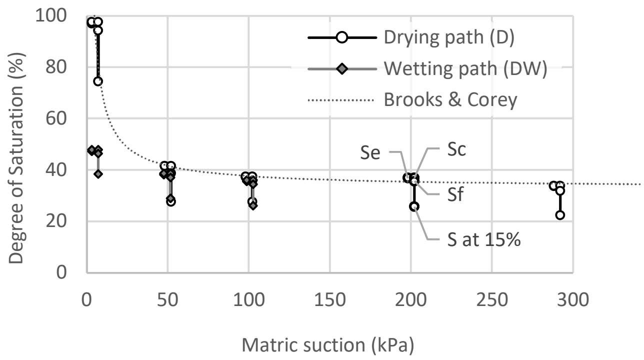

Figure 3. Degree of saturation paths in function of the matric suction during unsaturated shear after initial drying and initial drying-wetting. S_e, S_c, S_f and S at 15% represent values at equilibrium, maximum volume contraction, failure and 15% axial strain. Data points are slightly offset from their true matric suction to highlight the hydric trajectory throughout loading. An air-entry value of 4.7 kPa and a pore size distribution index of 0.86 gives the illustrated Brooks and Corey model.

3.4 Discussion of results

The characteristic curves presented in Figure c and Figure show that the column and axis-translation tests don't give the same results as those derived from the triaxial loadings. These differences may find an explanation in the preparation method of soil specimens. As earlier discussed, examination of sample photos reveals the presence of a network of large voids on their surface (Figure a and b).

Changes were introduced to sample preparation after noticing fissures on the high air-entry porous stone at the base pedestal following a preliminary triaxial test of the experimental program. This created an air pressure leak, hindering the application of the matric suction. Cracking was attributed to excessive concentration of the axial loading force at coarser grains contact points against the porous stone. The addition at the top and bottom of 5 mm thick fine particle soil layers fixed this problem. Subsequent study of photos of the modified specimens indicates that this change in their preparation for triaxial testing led to eliminate large voids at both extremities (Figure b). Examination of the samples after applying confining stress in the triaxial cell also showed that the membrane clung to their perimeter surface, which could have closed the bigger voids. In their absence, water retention would rise. This may explain the differences between results reported in Figure c and Figure . According to the latter figure, the specimens used for triaxial loading may feature an air-entry value in the order of a few kPa and a water-entry value under 5 kPa. Considering the steep desaturation gradient observed on samples in column tests (Figure c) that typically exhibit sands (Lu & Likos, 2004), the residual matric suction of triaxial specimens should be below 50 kPa. The modelled Brooks and Corey drying characteristic curve illustrated in Figure appears to confirm this.

3.4.1 Water drainage while shearing during both contraction and dilation phases

As observed for saturated shear tests, the material in the unsaturated state should intuitively drain during the volume contraction phase. Then absorb water throughout the subsequent dilation phase. Conversely, the contraction phase should decrease pore size, thus elevate capillary rise (or the degree of saturation) and yield water absorption while the dilation phase should act inversely. However, the findings don't appear to agree with either reasoning. In all but two tests (DW05 and D100 in Figure c), drainage occurs in both the initial phase of contraction and pursues even so during the dilation phase. This behaviour appears contradictory and counter-intuitive.

As outlined in the introduction, evidence shows that a relationship exists between the SWCC and the void ratio where for a set matric suction, the higher the void ratio, the lower the degree of saturation. This should prove true for triaxial tests of this study. At the onset of loading up to the maximum volumetric contraction of the sample (from “e” to “c” along the black line of Figure as shown for the drained shear at 5 kPa matric suction), the degree of saturation rises as the void ratio decreases. The former reaches its peak when the latter attains its minimum. These results agree with the earlier underlined evidence. The observed increasing degree of saturation of the contraction phase corresponds to what a “wetting cycle” produces. From this point forward, further shearing generates dilation (Figure b). This increases the void ratio resulting in a similar inverse relationship where the degree of saturation declines (Figure). This decreasing volumetric water content indicates that the dilation phase engages a “drying cycle.” To summarize, loading a soil that contracts and then dilates first generates wetting that reverses into drying. All tests of this study confirm the same trend.

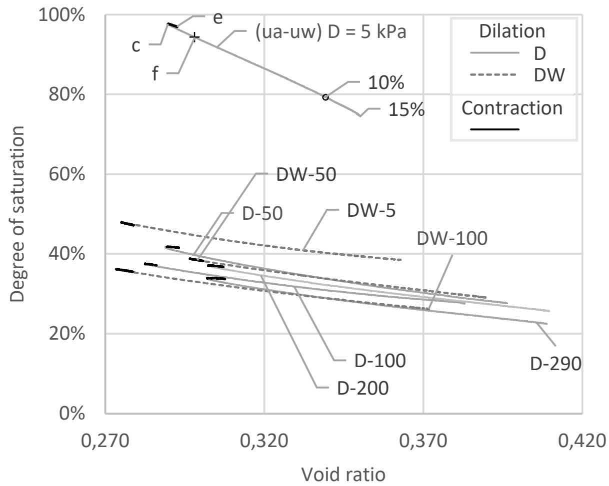

Figure 4 Degree of saturation in function of the void ratio during CD triaxial testing: shearing progresses from starting point “e” along the solid black line towards the maximum volume contraction point “c,” then along the grey line (solid for shearing after drying path, dashed for after drying-wetting path) through the failure point “f” and ends at 15% axial strain.

During shear, the decreasing capillary retention created by the rising void ratio would explain why observed drainage occurs throughout dilation (moving along the solid grey line segment of Figure). Then why does drainage occur during the contraction (“wetting”) phase? The answer may rest in the hysteresis of soil water retention. During the contraction phase, voids decrease in volume and increase capillary rise, as characterized by the increasing degree of saturation (black lines from “e” to “c” of Figure). On the other hand, contraction implies that the water volume occupies a larger part of the voids, yielding a degree of saturation that may exceed the retention capacity of the soil. Forcefully, this excess water (that pushes pore water pressure to rise and thus decreases suction) must drain to maintain equilibrium with the soil-water retention capacity and the set matric suction. This may explain why drainage also arises during the contraction phase of CD loadings. Wetting also means a smaller solid-liquid contact angle (Lu & Likos, 2004). Hence, for the same void ratio change during drained shearing, the absolute value of the retention increment should prove smaller for wetting (contraction phase) than during drying (dilation phase). Thus, while shearing under a constant matric suction, the water retention curves expressed as a function of the void ratio should display a steeper slope during dilation than for the contraction phase. Results of this study appear to confirm this hypothesis (Figure).

One final point regarding this topic deserves attention. The earlier presented paths of the degree of saturation during loading of Figure thus translate into curvilinear trajectories when displayed in function of the void ratio (Figure). As a result, drained shear tests follow a path on a surface defined in S-(u_a-u_w)-e space (omitted due to lack of space). Many authors have observed and developed models for such a surface from isotropic consolidation data obtained under a constant matric suction (see those reported by Gallipoli and Bruno 2022). As hypothesized by Mašín (2010), it appears this study confirms that the water retention surface model applies to drained shear performed at a constant matric suction. However, this research highlights that dense materials express a non-monotonic hydric cycle with wetting followed by drying during shear. Hence, a transition model seems necessary to bridge from the wetting only surface to the drying only one.

4 Conclusion

Two types of specimens were prepared with the same sand and gravel an 8.9% silt content (SW-SM). The first displays large pores on their surface (up to 6 mm in width), creating what appears as a double porosity material. Column and axis-translation tests served to establish the soil-water characteristic curve. Measurements show an abrupt desorption gradient at a matric suction of 0.55 kPa and a residual value below 10 kPa. In sorption, the water-entry value is under 5 kPa. Interestingly, the samples turn out unsaturated during desorption even at the lowest measured matric suction of 0.14 kPa. Moreover, up to a matric suction of 0.55 kPa, they display a constant 74% degree of saturation. The analysis puts forward an explanation based on the existence of a maximum pore size capable of maintaining saturation by capillarity. Given the large voids of the studied specimens, this should lead to create an air-entry value under 0.05 kPa. This would explain the observed unsaturated state even at the lowest measured matric suction. This paper provides arguments on why practical considerations don't permit to determine a representative water content at such a low matric suction. It also appears likely that certain coarse grain soils (such as rockfill or riprap) with pores beyond the capillary length size should display a null air-entry value. This characteristic could offer interesting implications on the hydraulic conductivity in the unsaturated state and for groundwater flow such as in a capillary barrier.

The absence of a macro-porosity effect in the second specimen set (used in triaxial shear) seems to yield a single mode statistical void size distribution. They present an air-entry value in the order of 5 kPa, a residual matric suction below 50 kPa and a matric suction under 5 kPa for the water-entry value. Drained triaxial loadings performed at a constant matric suction gives no effective cohesion, a friction angle of 43.6° and a ϕ^b angle of 42.5 °.

Loading the granular material after desaturation by drying produces drainage during both contraction and dilation phases. This appears the result of the relationship between the void ratio and the soil-water retention capacity. As the soil contracts, the latter increases as void sizes decrease (implying wetting and a rising solid-liquid contact angle). Although the decreasing void ratio permits water to occupy a larger fraction of void space, it appears that it squeezes water volume towards exceeding the capillary retention capacity. This excess water needs to outflow, yielding drainage during contraction. As for the dilation phase, the increasing void size decreases capillary retention giving a smaller fraction of void space for water to occupy. Some water volume must thus exit to maintain equilibrium with the soil-water retention capacity. This would explain why drainage continues during dilation.

This study confirms that like with the matric suction (u_a-u_w), the degree of saturation inversely correlates to the void ratio and follows a path on a soil-water characteristic surface (SWCS) during shear. During the initial contraction phase, the water regime leaves the drying SWCS and moves along a transitional surface towards its wetting counterpart. Subsequent dilation then migrates the water regime back to the drying SWCS. Hence, performing shearing after initial drying on dense (with dilatancy) granular materials through constant matric suction CD tests permits observing their transitional SWCS and characterize their drying SWCS. Isotropic loading that contracts deformable ground, on the other hand, such as loose granular materials (or normally consolidated fine-grained soils) decreases the void ratio and causes soil-water retention capacity to rise. This equates to wetting. Such tests may thus prove well suited to model water retention while shearing loose soils since they contract and wet during loading. The cases of Kaolin Speswhite reported in the introduction falls in this latter category. This leaves to investigate loading paths where soils contract and dry and where they dilate and wet. With this knowledge, any loading conditions (such as undrained, constant void ratio and constant water content tests) could be solved. This will require further research.

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