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An Investigation into the Water Retention Behaviour of an Unsaturated Natural Fissured Clay

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Abstract: The presence of intensely fissured soils is often found to relate to high geotechnical risks, such as landslide risk. This is especially the case of the Southern Apennines, Italy, where slopes formed of intensely fissured clays are frequently affected by landslides. The latter are generally triggered by rainfall infiltration, which takes place through the outcropping, unsaturated clayey soil cover. With the final aim of reducing landslide risk in areas covered by fissured clays, a detailed hydro-mechanical characterisation of these materials is required. While the behaviour of fully saturated fissured clays has been investigated in the last decade, only a few studies dealing with unsaturated, natural fissured clays are reported in the literature. The present paper aims to give a contribution toward filling this gap by extending an investigation campaign started a few years ago on the Paola Doce fissured clay outcropping on the Pisciolo slope (Southern Apennines, Italy). The physical properties of the material and some of its key micro- to meso-structural features are first analysed, the latter also based on Scanning Electron Microscope (SEM) micrographs of an undisturbed sample taken at 1.4 m depth on the Pisciolo slope, which is mainly formed of Paola Doce clay. Subsequently, water retention data of the soil are presented, which were obtained using both high-capacity tensiometers and the filter paper technique. These data were collected not only on undisturbed samples but also while subjecting the same material to drying paths. The results herein reported aim to make a link between the water retention behaviour of the Paola Doce clay sampled at Pisciolo and its fissured structure.

Keywords: natural fissured clay; unsaturated soil; filter paper; tensiometer; water retention curve

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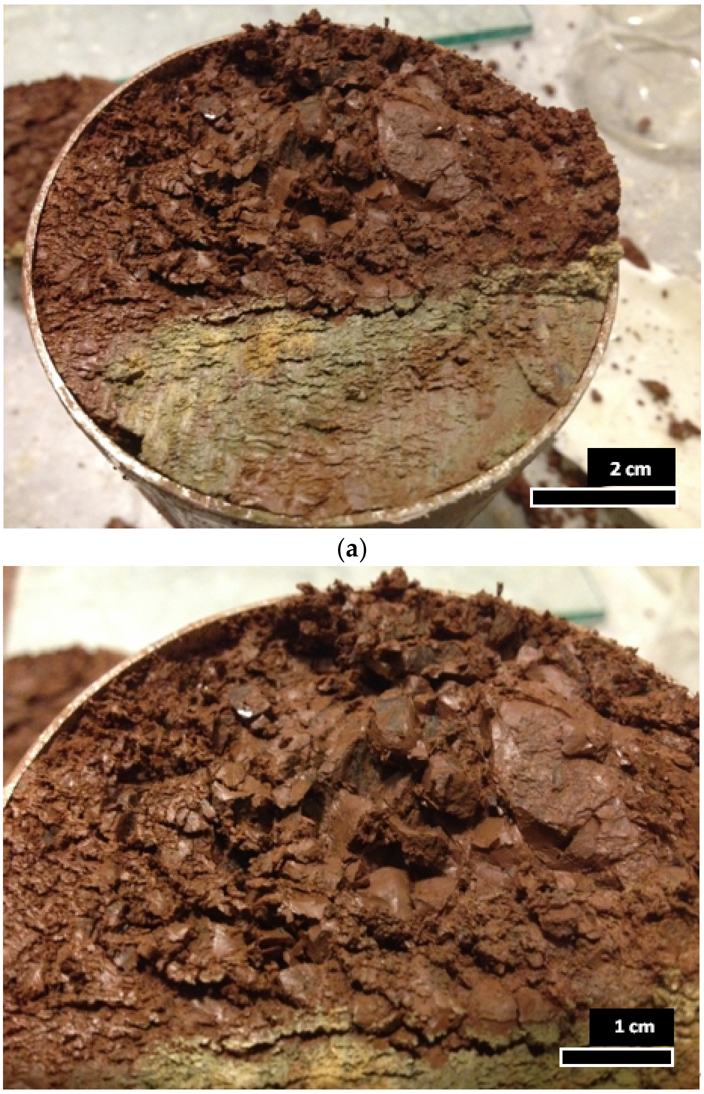
1. Introduction

The presence of formations with a complex structure [1], in particular those mainly including intensely fissured clays, often represent a slope internal factor [2] of landslide risk [1–8]. Intense fissuring, in fact, determines: (i) a shear strength lower than the one characterising the same material when reconstituted and (ii) a higher saturated permeability, as shown in [9–11] with reference to intensely fissured clays belonging to clayey flysch formations often forming unstable slopes along the Southern Apennines, Italy. In this area, the lower shear strength of the fissured clays represents an internal factor predisposing the slopes to failure as well as the higher saturated permeability of these materials [12–15]. The latter promotes rainfall infiltration, which is the main external factor triggering landslide phenomena [16–20]. Rainfall infiltration takes place through the shallow clayey cover, that is generally unsaturated, with suctions and water contents changing during the year due to the interaction between soil, vegetation and atmosphere [16–21].

A detailed investigation of the rainfall-induced landslide mechanisms taking place in the Southern Apennines, Italy, would require an accurate hydro-mechanical characterisation of the fissured clays outcropping on the slopes not only when fully saturated but also when partially saturated. While the hydro-mechanical behaviour of fully saturated fissured clays has been already thoroughly investigated [9,10,22–24], discussions about the behaviour of fissured clays when partially saturated have been rarely reported in the literature. In this respect, interesting contributions are provided, for example, by [25–27], but these studies refer to compacted and/or reconstituted fissured clays. The water retention behaviour of natural unsaturated fissured clays has not been investigated yet in great detail, except for a few contributions, including [12,13]. The latter present water retention data of the Paola Doce fissured clay outcropping on the Pisciolo slope (Figure 1), which is representative of the fissured clays often involved in instability phenomena in the Southern Apennines, Italy [12].



(b)

Figure 1. Undisturbed sample of Paola Doce fissured clay taken at 1.2 m depth at Pisciolo (**a**) and details of its meso-structure (**b**).

The present paper is intended to address this gap of knowledge by extending the study presented in [12,13]. First of all, some of the key micro- to meso-structural features of the Paola Doce fissured clay forming the slope cover at Pisciolo were analysed, also based on Scanning Electron Microscope (SEM) micrographs of an undisturbed sample taken at 1.4 m depth. Subsequently, water retention data of the same material obtained through laboratory tests are presented, showing how the state of the fissured clay herein analysed changes, during the year, as a result of its interaction with vegetation and atmosphere. Water retention data were collected not only on undisturbed samples (i.e., with reference to in situ conditions) but also while subjecting the same samples to drying paths. All these data were interpreted based on the preliminary micro- to meso-structural investigation reported in the paper, linking the water retention behaviour of the material to its fissured structure. The water retention data herein presented refer to suction measurements performed with two different methods, i.e., high-capacity tensiometers and filter paper technique, which are capable of measuring suctions up to around 1.8 MPa and 30 MPa, respectively [28]. A comparison between the results obtained with these two methods is also discussed with reference to some of the laboratory data reported.

2. Materials and Methods

2.1. Paola Doce Fissured Clay: Index Properties and Key Structural Features

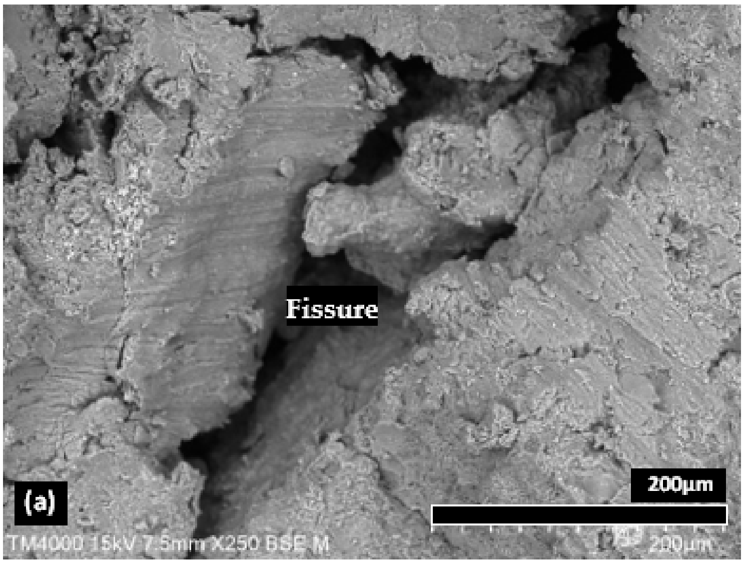
As more extensively discussed in [12], Cretaceous-to-Miocene turbidites form the unstable areas of the Pisciolo slope, where the Paola Doce fissured clay, belonging to the Paola Doce Formation, is outcropping. The physical and structural properties of this clay result from a complex geological history, which is mainly characterised by an initial sedimentation phase that took place in a pre-orogenic marine environment followed by a phase during which the material was heavily involved in the Apennine orogenesis. Due to its accumulation in a turbidite basin, the Paola Doce clay often interbeds isolated coarse lenses and fractured rock blocks, as documented by results of electrical resistivity surveys presented in [12]. Moreover, the Paola Doce clay is also characterised by an intense fissuring at the meso-scale, which has been extensively characterised in [12] and that resulted from the Apennine orogenesis, during which the material experienced significant faulting and folding. An example of the typical fissured meso-structure characterising the clayey slope cover at Pisciolo is shown in Figure 1, where the clay elements forming the material can be identified together with the fissures dividing them. As illustrated more clearly in Figure 1b, most of the clay elements have an average dimension ranging from a few to several millimetres. While visual inspections of the samples allow observing the presence of the fissures, the opening of the fissures can only be quantified by means of more detailed micro- to meso-structural investigations, such as those reported in [29].

The physical and hydro-mechanical properties (e.g., permeability, compressibility, strength) of the Paola Doce fissured clay forming the Pisciolo slope are summarised in [10,12,14], mainly focussing on the behaviour of the material when fully saturated, which is investigated by means of an extensive laboratory and field characterisation campaign conducted on undisturbed samples taken from ground level down to 80 m depth. The results of the soil classification activities carried out on these samples show that the material (clay fraction, CF = 37–62%; silt fraction, MF = 30–40%) is highly plastic (average plasticity index, PI, close to 40%) and very intensely fissured. A detailed characterisation of the fissuring intensity and orientation has been also performed [12] based on the fissuring characterisation chart proposed by [9], showing that the Pisciolo fissured clay (from ground level up to 80 m depth) presents a “very high” fissuring intensity (classified as I6 according to [9]) with either “random” or “single” fissuring orientation (i.e., classified as F3 and F1, respectively, according to [9]).

The laboratory data reported in the following refer to the Paola Doce clay outcropping in the southern portion of the Pisciolo landslide basin (named zone S in [12]), which was sampled at depths ranging between 0.7 and 1.6 m. The samples were extracted in different periods of the year in order to analyse how the state of the material evolves, with time, as a consequence of its interaction with vegetation and atmosphere. In particular, 16 samples were extracted by means of an on-purpose built ring kit [12] in the period from March 2012 to March 2013. Given that the research activities herein summarised refer to a specific portion of the Pisciolo slope (i.e., the clayey cover located in the southern area), the physical and micro- to meso-structural features of the material considered in the present study were characterised first, before proceeding with the filter paper technique and high-capacity tensiometer measurements subsequently discussed.

The material tested, sampled between 0.7 and 1.6 m depth, was classified as a clay (CF = 61%) of high plasticity (PI = 29.47%), whose index properties are consistent with those identified by [12] for samples also extracted at large depths. The key meso-structural features of the fissured clay herein considered were also identified based on the characterisation chart presented by [9] and following the procedure already adopted by [12], concluding that the material is generally "very highly" fissured (I6) with fissures of random orientation (F3), as it can be observed looking at Figure 1. The key micro- to meso-structural features of the material were also explored by taking Scanning Electron Microscope (SEM) micrographs of a sample extracted at 1.4 m depth in March 2012. The SEM micrographs were taken on sub-samples, while keeping the material under low vacuum pressures [30]. The material analysed with the SEM had a degree of saturation, S_r = 83.29% and a matrix suction, s = 1160.0 kPa (the matrix suction corresponds to the difference between pore-air pressure and pore-water pressure and was measured with high-capacity tensiometers according to the procedure described in the next section).

Three of the most representative SEM micrographs collected are shown in Figure 2, where the fissures splitting the material at the meso-scale are clearly identifiable. The information shown in Figure 2 allows estimating the opening of these fissures, that seem to fall broadly in the range 10–100 μm. This confirms what was simply inferred, so far, by visual inspections (see Figure 1b), i.e., that the Paola Doce clay at Pisciolo exhibits at least a double-porosity, which is represented by the pores located within the clay elements (i.e., the "intra-element" pores) and the fissures (i.e., the "inter-element" pores), similarly to what was observed by [25–27] for compacted scaly clays. It is worth highlighting that the opening of the fissures is expected to depend on the confining pressure and evolve during drying/wetting. Therefore, the information derived from Figure 2 should be considered representative of a specific stage of the structural variations that the material experiences, during the year, at 1.4 m depth, as a consequence of its interactions with vegetation and atmosphere.



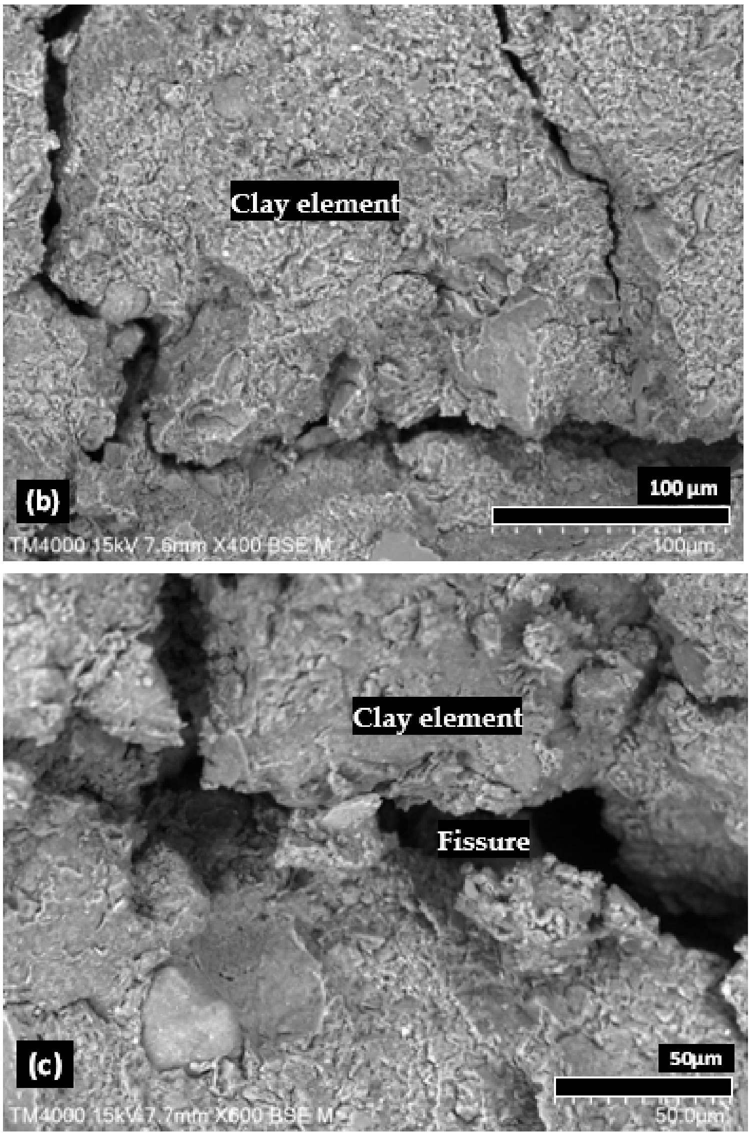


Figure 2. SEM micrographs at small to medium magnification of Paola Doce fissured clay ((**a**), 250×; (**b**), 400×; (**c**), 600×).

2.2. Suction Measurement Methods: Filter Paper Technique and High-Capacity Tensiometers

The water retention behaviour of the Paola Doce fissured clay has been investigated by measuring the degree of saturation, S_r, void ratio, e, and matrix suction, s, on undisturbed samples taken at depths ranging between 0.7 and 1.6 m. These values were measured just after sampling the material in different periods of the year to identify the in situ conditions and see how they change as a result of the interactions with vegetation and atmosphere. Moreover, S_r, e, and s were also measured while subjecting to drying paths 10 of the 16 samples analysed in the present study, to have a more comprehensive idea of the water retention behaviour of the Paola Doce clay over a larger suction range. Matrix suctions were measured by means of both the Imperial College London (ICL) high-capacity tensiometers [31] and the filter paper technique [32], according to the procedures discussed in the following. All suction measurements were performed after preparing, from the undisturbed samples, specimens of 50-to-56 mm diameter and 20-to-40 mm height (Figure 3).

Figure 3. Specimen prepared for suction measurements (50 mm diameter, 40 mm height).

Whatman No. 42 filter paper, neither pre-treated [32] nor pre-dried in the oven [33], was used to measure matrix suctions roughly ranging between 30 kPa and 30 MPa [33,34]. For each measurement, a couple of filter paper disks was put in contact with each of the two specimen bases (hence, four filter paper disks in total were used in every measurement). For each couple of filter paper disks, only one disk was in direct contact with the base of the specimen (referred to as "in-direct-contact" filter paper) and had to act as protection for the other disk (referred to as "protected-in-contact" filter paper) [35]. An equilibration time of two weeks was waited for each suction measurement [36], the latter derived by means of the calibration curve deduced by [37] using the pressure plate apparatus. From the two "in-direct-contact" filter paper disks, one average suction value was calculated. Similarly, one average suction value was derived from the "protected-in-contact" filter paper disks. Hence, every measurement was associated with two average suction values. Nevertheless, only the suction value obtained from the "protected-in-contact" filter paper disks has been considered in the present study, because the "protected" filter paper disks were certainly not contaminated with any soil "left-overs" (hence, they were likely to provide more accurate suction estimates).

ICL high-capacity tensiometers were also employed in the experiments, as previously mentioned. Before performing each measurement, the tensiometers were saturated according to the procedure proposed by [38] and then pre-pressurised according to the procedure reported in [39]. As shown in Figure 4, all the measurements were conducted by: (1) fixing the tip of the tensiometer in the centre of a Perspex disk laid on one base of the tested specimen; (2) spreading a kaolin paste on the ceramic tip of the tensiometer to guarantee full hydraulic connection with the soil; (3) wrapping in cling film all the sides of the specimen, except the one where the measurement was taking place, in order to avoid water evaporation from the soil. Most of the times, tensiometer measurements were repeated by performing them on both the two bases of the specimen, also adopting different tensiometers. In these cases, the matrix suction value reported corresponds to the average value obtained from the different measurements.

Figure 4. Example of high-capacity tensiometer measurement.

3. Results

3.1. State of the Material at Shallow Depths during the Year

In situ conditions of the tested fissured clay are herein reported in terms of both matrix suction, s (Figure 5a) and degree of saturation, S_r (Figure 5b) with reference to undisturbed samples taken at depths ranging between 0.7 and 1.6 m. The material was sampled from March 2012 to March 2013 in order to assess the impact of the soil–vegetation–atmosphere interaction on its state. In Figure 5a, filter paper measurements are referred to as FP, while ICL high-capacity tensiometer measurements are referred to as T. The results in the figure show that, at depths ranging between 0.7 and 1.6 m, the Paola Doce fissured clay presents matrix suctions roughly ranging between 27 and 1160 kPa during the year going from March 2012 to March 2013.

The state of the material at depths ranging between 0.7 and 1.6 m is very sensitive to weather variations, so the highest suction values, for instance, are not necessarily measured during the driest periods of the year, given that single, isolated rainfall events could easily affect general trends of suction variation [17]. Similarly, should rainfall events occur less frequently than expected during the wettest periods of the year, high suctions could also build up in seasons during which they are expected to be low. Despite the impact that short-term weather variations can have on the state of the outcropping soils, the data in Figure 5a seem to be in reasonable agreement with the general climatic features of the sampling periods. For example, except for a suction value measured in March 2012 with the tensiometers, the highest suctions, broadly varying in the range 195–680 kPa, were all recorded in August 2012. On the other hand, suction values lower than 195 kPa were measured in May 2012 and March 2013, with the lowest suction, of around 27 kPa, measured in 2013 at the end of winter. When looking at the data in Figure 5a, it is interesting to observe that at similar depths, the suction values measured with the filter paper technique are consistently lower than those measured with the ICL high-capacity tensiometers. Comments on the differences between the two suction measurement techniques herein adopted are reported in the following.

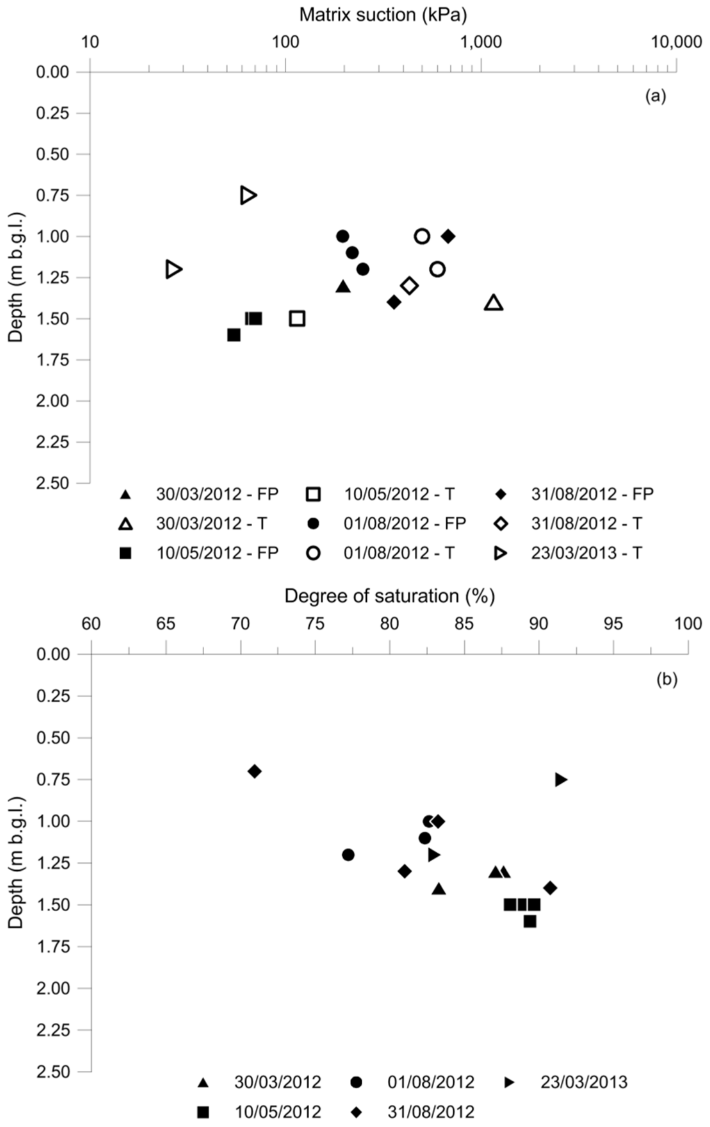


Figure 5. Water retention data of the Paola Doce fissured clay sampled at different depths and during different periods of the year: (**a**) matrix suction, measured with the filter paper technique, FP, and high-capacity tensiometers, T; (**b**) degree of saturation.

Similar to the matrix suctions in Figure 5a, also the degrees of saturation reported in Figure 5b show variations, with depth and time, that are generally consistent with the weather variations typically occurring during the year. For example, the lowest degrees of saturation were measured in August, with S_r broadly ranging between 70% and 83% (except for a single value close to 90%). On the other hand, all the S_r measurements conducted in March and May gave values roughly falling in the range 83–92%. It is interesting to observe that all the measured S_r values are much lower than 100% even when associated with relatively low suctions. Following the framework proposed by [40], who provided an interpretation of the water retention behaviour of multi-porosity materials, the presence of S_r close to 90%, even for suctions of a few kPa, could be mainly related to the desaturation of the fissures, as discussed more extensively in the next sections.

3.2. Typical Drying Paths of the Paola Doce Fissured Clay

After evaluating the initial state of the Paola Doce clay, 10 specimens were subjected to staged drying paths, with suction measurements performed, at the end of each drying stage, by means of both filter paper technique and/or ICL high-capacity tensiometers. The drying stages were imposed by allowing the specimens to be in contact with the atmosphere, so that the pore water could evaporate. However, even during drying, the material was covered (but not wrapped) with cling film to allow for a very slow and homogeneous drying process to take place across the specimens. In order to better discuss the typical behaviour exhibited by the tested fissured clay during drying paths started from in situ conditions, representative water retention data are reported in Figure 6, with reference to a representative specimen, named "Specimen 1". The data are shown in terms of matrix suction, s, against: degree of saturation, S_r (Figure 6a), void ratio, e (Figure 6b), and volumetric water content, ϑ_w (Figure 6c).

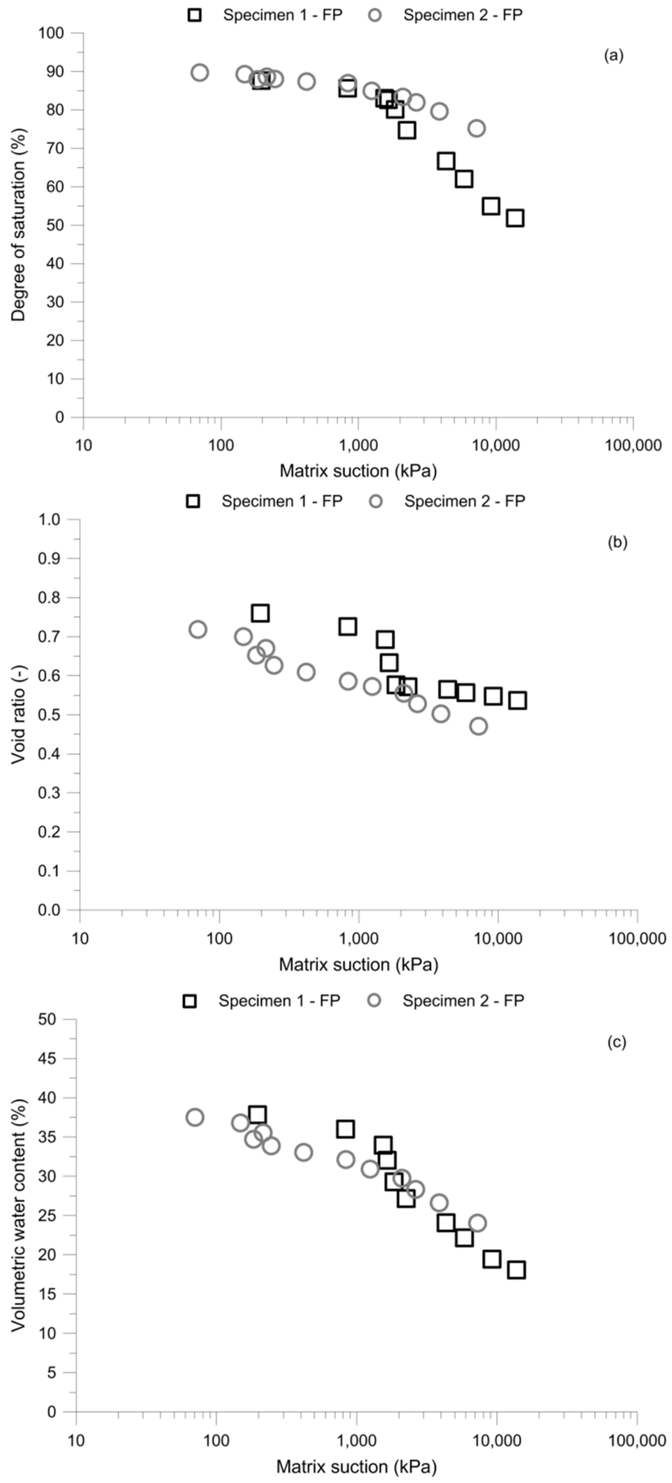


Figure 6. Representative water retention data of the Paola Doce fissured clay reported in terms of matrix suction (measured with the filter paper technique, FP) against: (**a**) degree of saturation; (**b**) void ratio; (**c**) volumetric water content.

In Figure 6a, it can be observed that S_r decreases slightly during the first two drying stages, even if the matrix suction increases of almost one order of magnitude. When s values of around 1000–2000 kPa are exceeded, the slope of the water retention curve increases significantly, showing a roughly linear response. Normally, s = 1000–2000 kPa would be interpreted as the "air-entry value" (AEV) of the material [41]. However, as previously observed, the desaturation of the tested fissured clay is expected to take place at very low suctions as a consequence of the water drained out of the inter-element pores (i.e., the fissures). Hence, due to the (at least) double-porosity structure of the material, the AEV "stricto sensu" is likely to correspond to very low suction values, while s = 1000–2000 kPa is likely to correspond to the AEV of the clay elements (shown in Figure 2). This interpretation seems to be corroborated by all the other water retention data shown in the following.

Figure 6b reports the water retention curve of Specimen 1 in terms of matrix suctions against void ratios. In this figure, a significant reduction in void ratio is observed at suctions of around 1000–2000 kPa, i.e., in correspondence of what has been interpreted as the AEV of the clay elements. For s > 2000 kPa, Specimen 1 shows very small void ratio reductions and a stiffness (herein defined as the ratio between matrix suction and volumetric strain) comparable with the one exhibited at the start of the drying path. It is interesting to notice that a similar behaviour was observed, for both reconstituted and natural clays, by [42,43], who referred to the abrupt reduction in void ratio as "volumetric collapse". Refs. [42,43] observed that the volumetric collapse not only occurs at the air-entry value, but also in correspondence of the yield point in isotropic compression. Such a correspondence can be also identified for other materials, such as the reconstituted silty clay tested by [44]. Isotropic compression tests were not performed on the Paola Doce clay sampled at Pisciolo at depths ranging between 0.7 and 1.6 m, so a similar correspondence between volumetric collapse, air-entry value and yield stress was not verified.

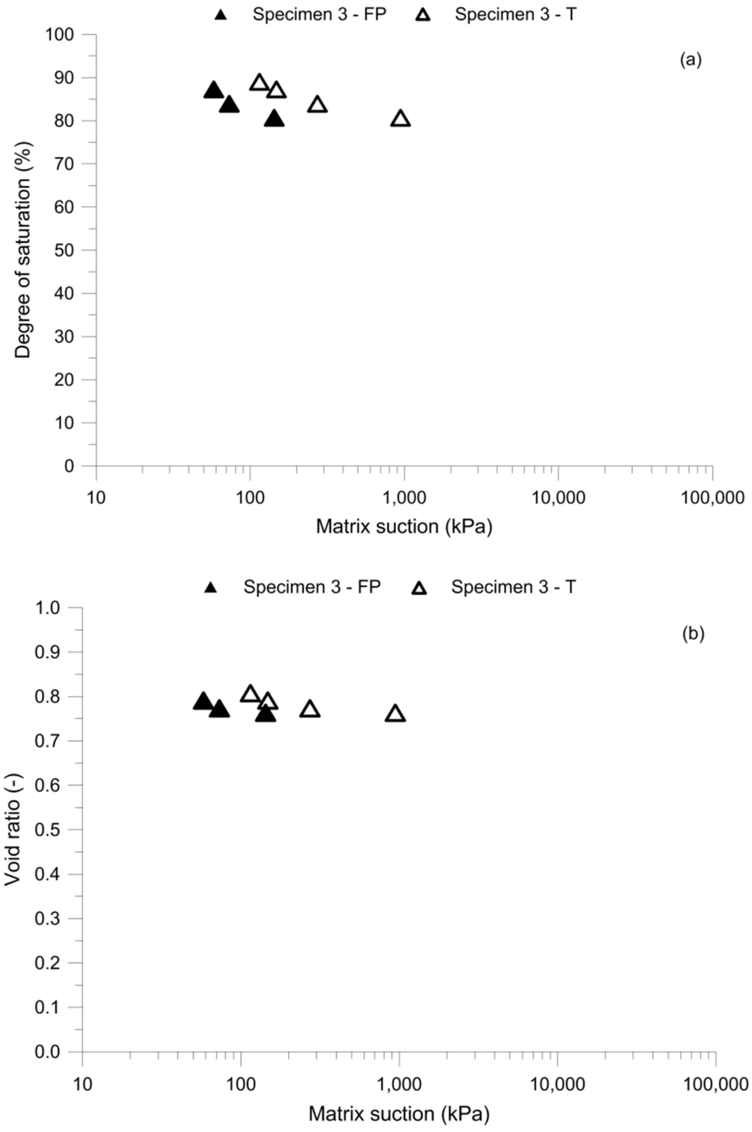
The water retention data of Specimen 1 are also reported in Figure 6c in terms of matrix suctions against volumetric water contents. The data in Figure 6c clearly reflect the variation in void ratio shown in Figure 6b, highlighting the presence of a major water content reduction at s = 1000–2000 kPa. Most of the specimens subjected to prolonged drying paths behaved like Specimen 1, exhibiting a volumetric collapse at suctions corresponding to the start of a major desaturation. However, a different behaviour was also observed, as for "Specimen 2", whose water retention data are shown in Figure 6 as well.

The S_r variations of Specimen 2 during drying (Figure 6a) are similar to those observed for Specimen 1 for s < 1000–2000 kPa. After this suction value, Specimen 1 shows a more abrupt desaturation, while Specimen 2 exhibits much milder S_r reductions. Based on the data in Figure 6a, it is more difficult to identify, for Specimen 2, the "intra-element AEV", which seems, however, equal or higher than the intra-element AEV of Specimen 1.

By looking at the data in Figure 6b, it is interesting to observe that not all the specimens experienced a volumetric collapse during drying. Specimen 2, for instance, exhibited non-linear but still relatively mild void ratio reductions from s ≈ 70 kPa up to s ≈ 7250 kPa. The different behaviour of Specimen 2 could be due to differences in structure or composition. It is also possible that Specimen 2 already experienced a volumetric collapse in the past due to a different stress history. As a matter of fact, Figure 6a shows that Specimen 2 has a more pronounced water retention capacity, the latter generally associated with a material having a smaller void ratio (such as a soil that already experienced major volumetric reductions). The different water retention behaviour of the two specimens taken as a reference can be also observed in Figure 6c, where the variations in ϑ_w with s are reported for both specimens.

3.3. Comparison between Filter Paper and High-Capacity Tensiometer Measurement Techniques

One specimen, named "Specimen 3", has been tested with both the filter paper technique and the ICL high-capacity tensiometers at each stage of the drying process in order to assess the impact of the measurement technique on the suction value determined. The data of Specimen 3 are reported in terms of matrix suction, s, against degree of saturation, S_r (Figure 7a), void ratio, e (Figure 7b), and volumetric water content, ϑ_w (Figure 7c). As observed for the data in Figure 5a, the high-capacity tensiometer measurements performed on Specimen 3 result in higher suction values than those obtained with the filter paper technique (Figure 7). This finding is in contrast with what has been reported by [45], who justified their results by making reference to the high salt concentration that characterised the pore water of the tested material. In fact, high salt concentrations are associated with high osmotic suctions, the latter potentially measured if there is no good filter paper contact or when S_r reduces significantly.



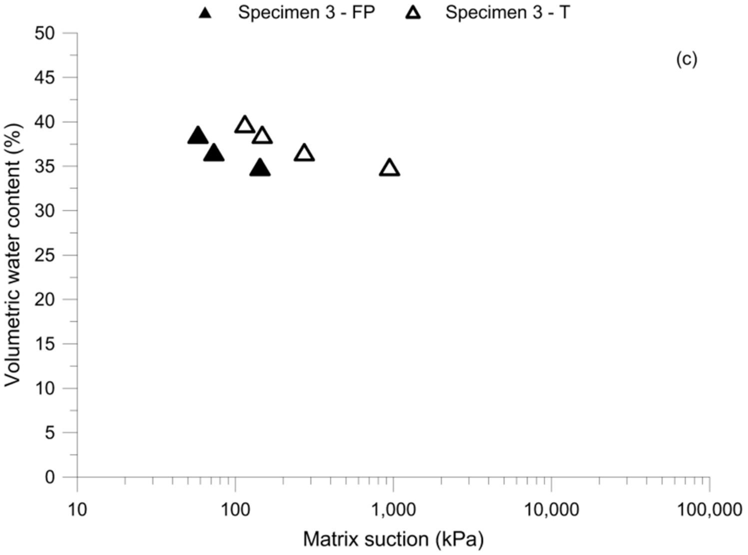


Figure 7. Water retention data of a specimen (tested with both the filter paper technique, FP, and high-capacity tensiometers, T) reported in terms of matrix suction against: (**a**) degree of saturation; (**b**) void ratio; (**c**) volumetric water content.

Further investigations are required in order to make a more comprehensive comparison between high-capacity tensiometer and filter paper measurement techniques. As part of the study herein summarised, in order to increase the reliability of the suction values determined with the tensiometers, the measurements were often repeated by putting a different tensiometer in contact with the second base of the specimen tested. For example, the highest suction value reported in Figure 7 corresponds to an average value obtained from measurements performed on the two bases of Specimen 3.

In order to better understand the extent to which the average value of the tensiometer measurements can be considered representative, it is interesting to observe in detail the results of each measurement conducted on each base, for instance with reference to the final drying stage of Specimen 3 (reported in Figure 8). The two measurements conducted on the two bases (named Base 1 and Base 2 in Figure 8) are significantly different, and this difference was also confirmed by repeating the measurements with different tensiometers (referred to as Measurements 1 and 2, for each Base, in Figure 8).

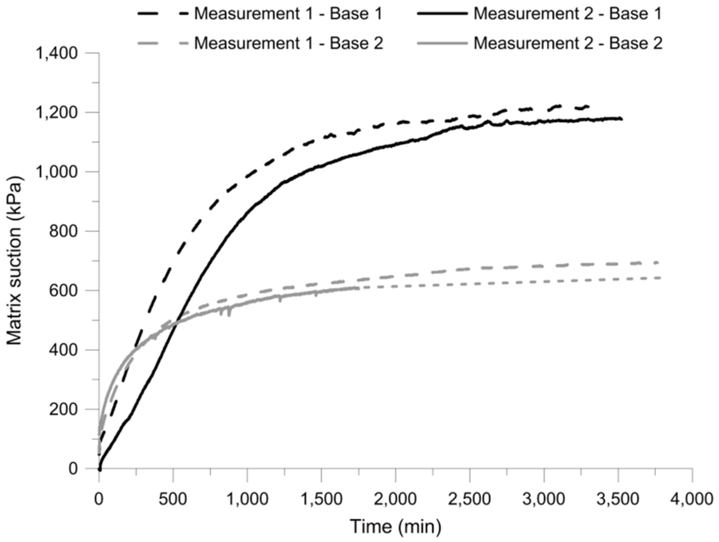


Figure 8. High-capacity tensiometer measurements conducted on Specimen 3 at the end of the last drying stage (the dotted segment is an extrapolation of the last measurement).

A tentative explanation of these findings could be provided by considering the meso-structural features of the material, potentially allowing the clay elements between the fissures to have a “near-independent” hydro-mechanical response during drying. This would mean that the tensiometer tips would be more likely to measure “local” suctions, which is not necessarily representative of the average value of the whole specimen. On the other hand, the filter paper disks would be able to measure more representative average suctions, being in contact with a bigger area of the specimen. Such an interpretation would be more sensible at lower degrees of saturation, such as the one characterising Specimen 3 at the end of the final drying stage (Figure 7a). As a matter of fact, a major desaturation of the fissures could reduce significantly the hydraulic connection between the clay elements, allowing them to behave like “specimens in the specimen”.

3.4. Drying Paths of all the Tested Specimens

In total, 10 of the 16 samples analysed in the present study were subjected to drying paths during which suction measurements were conducted (with either the filter paper technique or the ICL high-capacity tensiometers or both). All the data collected are reported in Figure 9 in terms of matrix suction, s, against degree of saturation, S_r (Figure 9a), void ratio, e (Figure 9b), and volumetric water content, ϑ_w (Figure 9c).

The initial degrees of saturation are consistently close to or lower than 90% (Figure 9a), supporting the idea, previously introduced, that the “first” air-entry value of the tested fissured clay (i.e., the “inter-element AEV”) is likely to correspond to very low suction values. This would imply that all the tested specimens probably had empty or almost empty fissures at the start of drying. The initial stages of the drying paths are characterised by S_r values that are scattered, but generally higher than 75–80%, until s = 1000–2000 kPa is approached. For most of the specimens, major S_r reductions are observed after this “second” air-entry value, which was previously identified as the stage at which air enters the intra-element pores (i.e., the “intra-element AEV”).

The data in Figure 9b show that the intra-element AEV (i.e., s =1000–2000 kPa) corresponds to a volumetric collapse for most of the specimens subjected to drying paths that reached high suction values. The data in Figure 9b also confirm that the volumetric collapse corresponds to a void ratio variation, Δe, close to or bigger than 0.1. It is interesting to notice that the smallest void ratios ($e \approx 0.45$) correspond to the values measured on Specimen 2, i.e., the specimen that did not show a volumetric collapse in drying (Figure 6b). It is also worth highlighting that for $s < 1000$ kPa, the specimens show a stiffness that is broadly comparable with the stiffness observed for $s > 2000$ kPa, when the material moves toward its shrinkage limit.

All the data collected on the specimens subjected to drying paths are reported in Figure 9c in terms of s-ϑ_w. As previously observed with reference to the data reported in Figure 6c, the volumetric water content variations reflect the variations of the data shown in Figure 9a,b. The highest ϑ_w measured, not corresponding to fully saturated conditions, are close to 42.5%, while the lowest values are close 10%. The latter, achieved after prolonged drying stages, correspond to suctions close to or slightly bigger than 30 MPa, which can be considered as the upper limit for matrix suction measurements performed with the filter paper technique, according to [33,34].

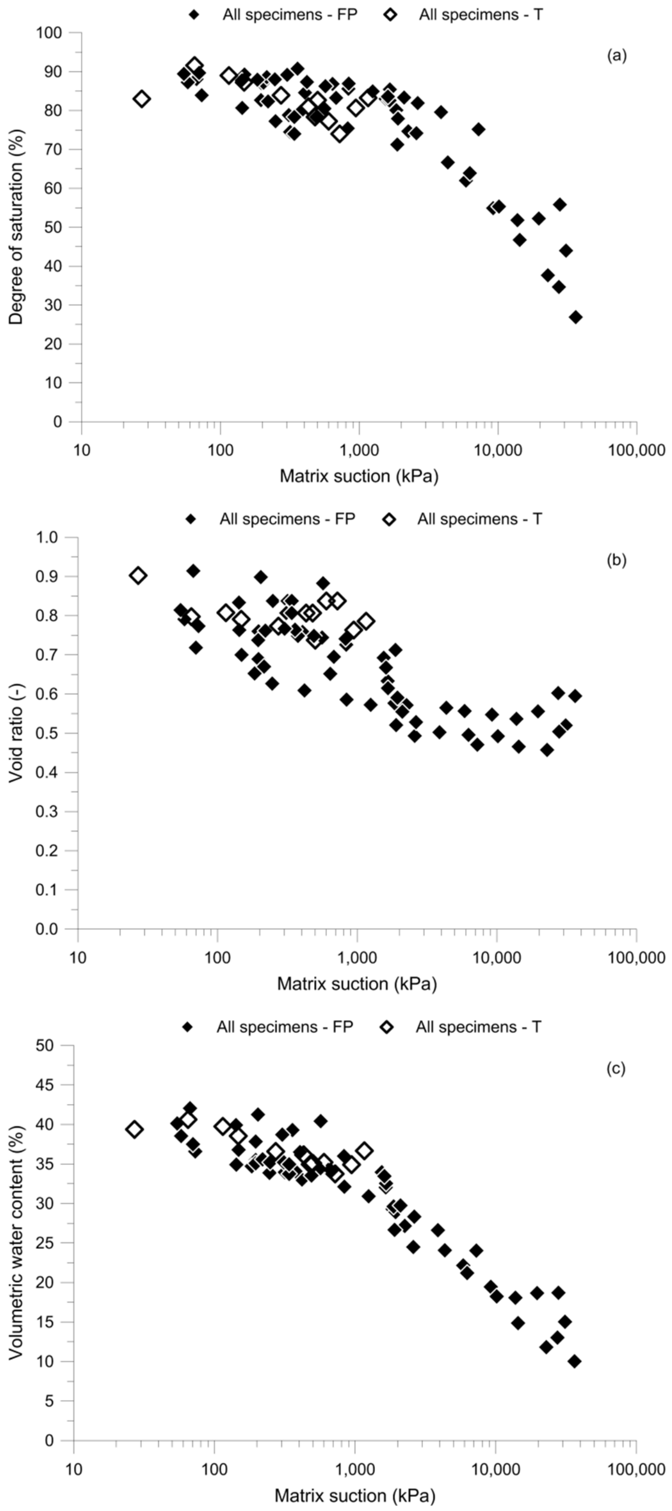


Figure 9. Water retention data of all the specimens (tested with both the filter paper technique, FP, and high-capacity tensiometers, T) reported in terms of matrix suction against: (**a**) degree of saturation; (**b**) void ratio; (**c**) volumetric water content.

4. Discussion and Conclusions

The present paper reported and discussed data that allowed characterising the hydro-mechanical behaviour of a natural unsaturated fissured clay, i.e., the Paola Doce clay outcropping at Pisciolo (with specific reference to the soil sampled between 0.7 and 1.6 m depth, i.e., the material forming the clayey slope cover). The micro- to meso-structural features of the material were first analysed, also based on Scanning Electron Microscope (SEM) micrographs taken on an undisturbed sample extracted at 1.4 m depth. The SEM images allowed estimating the opening of the fissures (broadly in the range 10–100 μm) that split the material in clay elements (most of them from a few to several millimetres in size), confirming that the Paola Doce clay exhibits at least a double-porosity, represented by the "intra-element" and the "inter-element" pores (i.e., the fissures).

Water retention data of the Paola Doce fissured clay at Pisciolo were also presented, showing how the state of the material located at 0.7 to 1.6 m depth changes, during the year, as a result of the soil–vegetation–atmosphere interaction. Despite the impact that short-term weather variations can have on the state of the outcropping soils, both matrix suctions and degrees of saturation seemed to be in reasonable agreement with the general climatic features of the sampling periods (i.e., March 2012–March 2013). For example, almost all the highest suction values (>195 kPa) were recorded in August 2012, while the lowest suction (≈27 kPa) was measured in 2013 at the end of winter. Similarly, the lowest degrees of saturation were measured in August (generally $S_r \approx 70–83\%$), while $S_r \approx 83–92\%$ was measured in March and May.

Water retention data were collected not only on undisturbed samples (i.e., with reference to in situ conditions) but also after preparing specimens that were subjected to drying paths. All these data were interpreted based on the preliminary micro- to meso-structural analysis presented, trying to make a link between the water retention behaviour exhibited by the Pisciolo clay and its fissured structure. Based on the data currently available, it is believed that the desaturation of the material takes place at very low suctions as a consequence of the water drained out of the fissures (i.e., the "inter-element pores"). This can be interpreted as the "first" air-entry value (AEV) of the material (i.e., the "inter-element AEV"), followed by a "second" air-entry value, which is associated with the start of major S_r reductions, identified as the stage at which air enters the intra-element pores (i.e., the "intra-element AEV"). For most of the samples subjected to a prolonged drying that reached high suction values, the "intra-element AEV" was observed for s = 1000–2000 kPa, in conjunction with a major reduction in void ratio (i.e., a "volumetric collapse").

The water retention data presented in this paper refer to suction measurements performed by means of two different methods, i.e., high-capacity tensiometers and the filter paper technique. A comparison between the results obtained with these two methods was also presented, showing how, for the tested material, the high-capacity tensiometers were recording suction values consistently higher than those measured with the filter paper technique. Even though more extensive investigations are necessary in order to fully understand the reasons behind these differences, a tentative explanation of these findings was provided by considering the fissured structure of the Paola Doce clay outcropping at Pisciolo, potentially allowing the elements between the fissures to have a "near-independent" hydro-mechanical response during drying. This would imply that the tensiometer tips would be more likely to measure "local" suctions, while the filter paper disks would be able to measure more representative average suctions, being in contact with a bigger area of the specimen.

The present work aimed to make a link between the water retention behaviour shown by the Paola Doce clay outcropping at Pisciolo and its fissured structure, which is characterised by at least a double-porosity. In order to corroborate the preliminary interpretations herein summarised, further micro- to meso-structural investigations would be necessary, for instance by analysing the pore size distribution of the material and how it evolves during drying. The response of the Paola Doce clay when subjected to wetting paths should be also studied in detail in order to have a more comprehensive idea of the hydro-mechanical behaviour of the material when partially saturated. A more detailed characterisation of the material would allow for more accurate slope–vegetation–atmosphere interaction analyses, the latter needed in order to improve slope movement predictions and, in turn, reduce landslide risk. Further developments of the research activities summarised in the paper would also have a wider positive impact on the scientific community, considering that the hydro-mechanical behaviour of fissured geomaterials, especially when partially saturated, has not been investigated yet in detail. This would allow better tackling situations in which a high geotechnical risk is associated with the presence of fissured soils.

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