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Study of the volumetric behavior of a residual tropical clay

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Abstract

This paper focuses on the volumetric behavior of residual tropical soils. Two residual tropical soils belonging to the same geological formation and located in the coastal sedimentary basin of Gabon are studied. These soils are known as pelitic soils. As the hydromechanical behavior of residual tropical soil is still relatively unknown, it is interesting to study the influence of soil suction on the volumetric behavior of the residual tropical soil through shrinkage curves. The purpose of this study is twofold. First, to study volume variations in the two tropical residual soils. Secondly, to propose a modelling of the soil-water retention curves (SWRCs) of these soils. For this purpose, drying tests are carried out to study the volume variations of the soil. These tests are supported by determining a bi-linear model to enable the variation in suction during drying to be estimated. Tests to determine SWRCs at different initial dry densities are used to calibrate the bi-linear relationship between void ratio, suction. The modified Kovács model (MK model) has been adapted to model the SWRCs of the studied soils.

Keywords: , Air entry value, residual tropical soils, water retention curves, void ratio, shrinkage test

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1. Introduction

In tropical regions, residual soils are often used in civil engineering works, especially for the construction of road and railway infrastructure. Residual soils result from the in-situ physical and chemical alteration of a parent rock (sedimentary, magmatic or metamorphic rock). They are soils with little or no transportation that are found close to the basin of their parent rock. According to [1], with the alteration process, their inter-particulate bonds and cementing are generally broken, which gives these soils a complex structure that can make them difficult to study.

For a long time, the study of residual soils focused mainly on the characterization and classification of these soils [1]. According to their degree of alteration, one thus distinguishes categories varying from *I* to *VI*, starting from fresh rock to completely altered residual soil [2]. Recent studies conducted by [3] extended current knowledge of their shear strength and compressibility. [4] studied the effect of the weathering process on the compressive strength of a clayey rock.

While the shear and compressibility behavior of residual tropical soils is beginning to be known, the hydromechanical behavior is still relatively unknown partly because most of geotechnical engineering techniques were developed for soils in temperate regions and are sometimes unsuitable for direct application to residual tropical soils [1]. According to [5], certain types of residual tropical soils (allophanic, plinthite, and lateritic soils) are sensitive to drying and others to remolding. On some of these soils, drying increases inter-aggregate cementing due to the dehydration of hydric cementing agents (halloysite, allophane), and the oxidation of sesquioxides. This results in a decrease in the clay fraction and thus in the plasticity. [5] also explains that remolding has rather the opposite effect on the plasticity of residual tropical soils. Remolding induces a degradation of the aggregates formed by the clay particles, which induces an increase in the fine fraction and thus plasticity. According to [6], the sensitivity of residual tropical soils to drying comes from the fact that these soils contain crystallized water in the mineral structure. This water depends on the mineralogical com-

position of the soil and is released if the soil is dried at high temperatures of $105^{\circ}C$. For these types of tropical soils, drying at lower temperatures ($50^{\circ}C$) or in the air is recommended. According to [7], residual tropical soils generally have liquid limits between 40% and 70% and plastic limits between 25% and
35 50%.

Since suction can greatly affect the mechanical behavior of these soils, it appears important to investigate their water retention property. The study of unsaturated soil behavior requires an understanding of water retention characteristics such as SWRCs. These curves describe the change in soil suction (ψ)
40 during drying or wetting paths with saturation degree (S_r) and water content (w), in the (ψ, S_r) and (ψ, w) planes. The use of the $S_r(\psi)$ representation of SWRCs is the most rigorous and practical for general applications [8].

Soil volume variations are generated by external factors such as mechanical stresses and water stresses (wetting/drying processes) [9]. In regard to water
45 stresses, non-deformable soils or incompressible soils are soils for which suction does not induce a volume change, the void ratio remains constant during the wetting or drying process. The SWRCs can then be easily described by the representation $S_r(\psi)$ or $w(\psi)$. For deformable soils (compressible or shrinking soils), the variation in suction induces a change in soil volume. The void ratio
50 becomes dependent on the suction. In this case, the $S_r(\psi)$ or $w(\psi)$ representations are not sufficient to describe the soil volumetric behavior. Knowledge of the dependence of SWRCs on dry density is therefore necessary for an adequate characterization of the hydro-mechanical behavior of deformable clays [10].

[11] and [12] found that in the plane $(\psi - w)$, with increasing initial dry
55 density, the desorption rate (drainage path) decreases and the residual moisture content increases. The shape of the SWRCs of fine-grained soils depends on the compressibility, stress state, compaction energy, and soil structure [13]. [9], [14] and [15] investigated the water retention capacity of clayey soil and found that the SWRCs for different dry densities was independent of dry density beyond a
60 certain matric suction. This is due to the fact that in the range of high suctions (close to dry), water is retained by the intra-aggregate pores, in which suction

is no longer governed by the effects of capillarity but rather controlled by the mineralogy of the soil and by the specific surface of the particles.

[16] have also shown that the effect of dry density on soil-water retention
65 behavior was strongly dependent on the microstructure. They studied the effect
of dry density on the water retention and microstructure of Boom clay using
the vapor equilibrium technique and mercury intrusion porosimetry tests, re-
spectively. The results showed that the SWRCs in the low suction range were
governed by the inter-aggregate pores, while those in the high suction range
70 were governed by intra-aggregates pores. [17] also indicate that soil tightening
(by compaction or consolidation) induces a reduction in macropore volume but
has a negligible effect on micropore volume; this has an effect on the slope of
the water retention curves.

Change in moisture induces soil deformation (swelling and shrinkage) gov-
75 erned by moisture migration within the microstructure [18]. The microstructure-
dependency moisture exchange is related to the capillary properties of soil, gran-
ulometry, mineralogy and compaction state. The microstructure and mineralogy
of residual tropical soils are associated with modes of soil formation by Physical
breakdown and chemical reactions [19].

80 This study aims to investigate the SWRCs of residual soils, the effect of dry
density and more particularly their volume behavior when they are subjected
to drying. The filter paper method was applied to measure the matric suction
of two residual tropical soils belonging to the same geological formation. These
soils are known as pelitic soils. A modeling of the SWRCs of these soils with the
85 modified Kovács model (MK model) is carried out to verify if this prediction
model for the SWRCs of these residual soils is practicable. On the basis of
the results obtained, a link between the air entry value and the void ratio for
these soils has been established. Thus, it is possible to estimate suction as a
function of the void ratio and the saturation degree using the Brooks and Corey
90 [20] relationship. These suction values are taken into account to determine the
curves that describe the volumetric behavior of the soil during drying.

2. Material and methods

2.1. Material

This study concerns two residual tropical soils (ARG1 and ARG2) belonging
95 to the same geological formation. These soils are known as pelitic soils. This
type of soil comes from a clayey sedimentary rock with fined grains, called
'pelite'. Pelite comprises siliclastic elements consisting mainly of silts (particles
between $4\mu m$ and $62\mu m$) and clays (particles smaller than $4\mu m$) [21]. The
materials that we are studying are residual tropical clay of weathering grade
100 *VI*, with fairly high percentages of clays (greater than 50%).

These soils were sampled from different locations on the main railway line
in Gabon, at intervals of about $2km$ in the longitudinal direction. They were
recovered from sampling pits; these materials constitute the subgrade material
of the railway line. These soils are present in the Gabon coastal sedimentary
105 basin (Figure 1), more precisely on the lands belonging to the Kango Formation
(included in the cocobeach group). These are lands formed in the Lower Cre-
taceous age (Neocomian to Barremian). According to [22], because of the type
of local climate in which they evolve, these soils are known as predominantly
ferralitic soils.

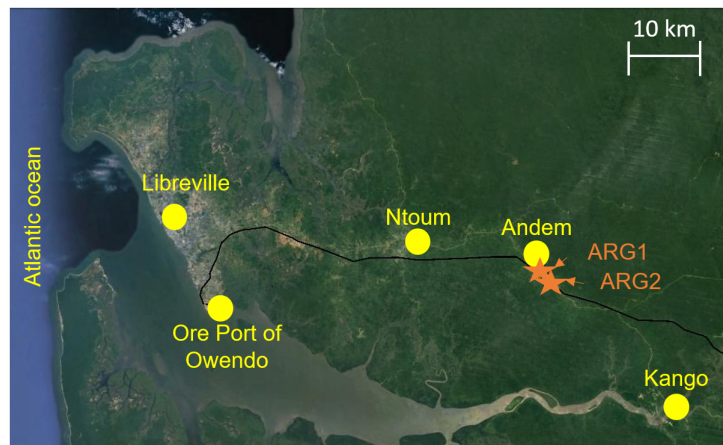


Figure 1: Location of the sampling sites: about $60km$ from the Gabon capital.

110 The results of the laboratory identification and characterization tests carried out on each of the samples are presented in Table 1. The materials were classified according to the French standard classification NF P 11 – 300 [23].

Soil	ARG1	ARG2
GTR French Classification	A3	A4
USCS Classification	MH-OH	MH-OH
Liquid limit, LL (%)	78.90	91.30
Plasticity index, PI (%)	38.50	50.60
Percent fines (%)	92.65	81.06
Specific gravity, G_s	2.70	2.70
Optimum water content, w_{opt} (%)	19.97	16.21
Maximum dry density, ρ_{dmax} (t/m^3)	1.65	1.66

Table 1: Physical characteristics of the samples studied

Figure 2 shows the Modified Proctor curves and the grain size distribution curves of the two materials studied. It is of note that the clays studied are very plastic with high liquid limit values and plasticity index values. Figure 2b shows that both clays have a fairly high percentage of clay particles (smaller than $2\mu m$), i.e. 76% clay for the ARG1 and 58% for the ARG2, with a spread particle size distribution. The top part of the subgrade soil consists of a mixture of fine-grained soil and lateritic gravel constituting the old foundation layer of the railway. Therefore, a proportion of gravel is included in the sampled materials. The grain size distribution curves show that the proportion of gravel is higher in ARG2 soil than in the ARG1 soil. For the remainder of this work, we used materials with diameters less than $2mm$.

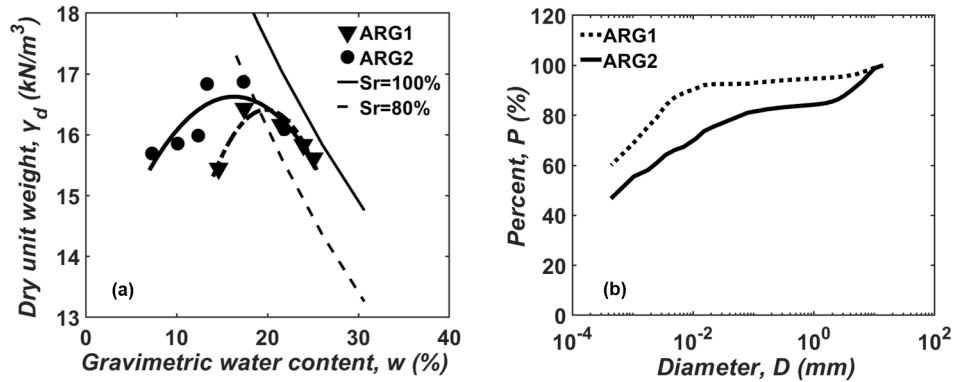


Figure 2: (a) Modified Proctor curves; (b) Grain size distribution curves.

2.2. Methods

2.2.1. Filter paper test

In order to obtain the SWRCs, the filter paper method is one method currently used ([24]; [25]; [26]; [27]; [28]). It consists of determining the suction of the filter paper in hydraulic equilibrium with a soil sample. This is an indirect measurement of soil suction. This method enables suctions of up to 30MPa to be measured. The filter papers used are Whatman No.42 and Schleicher and Schuell No.589. However, Whatman No.42 filter paper is rather more reliable ([24]; [28]).

In order to determine the SWRCs, the filter paper method was applied on soil samples compacted in PVC tubes. The materials used for this test were initially exposed to air and had begun to dry and form clumps. Each soil was manually crushed to prevent excessive disintegration and sieved at 2mm. The sieve was placed in the oven for complete drying for 24 hours at 105°C. These tests were carried out according to the [29] procedure using the initially dry Whatman No.42 filter paper. Tests were carried out for different initial dry densities to study the effect of dry density on the SWRCs and to establish the relationship between the air entry value and the initial void ratio. Table 2 shows the compaction characteristics of the samples. The Percent of Modified Proctor Optimum (MPO) is also shown.

To verify the drying sensitivity of these soils, a checking of the difference in
 145 water content obtained by drying at different temperatures was made. It was
 verified that the materials studied are not sensitive to drying by drying part of
 each of them at different temperatures as proposed by [6]. The results obtained
 are presented in Figure 3. We can see that the difference in water content
 between drying at 40°C and 105°C for these materials is about 3%. This shows
 150 that the materials studied are not sensitive to drying and that we can therefore
 raise the temperature up to 105°C to dry the material in the oven.

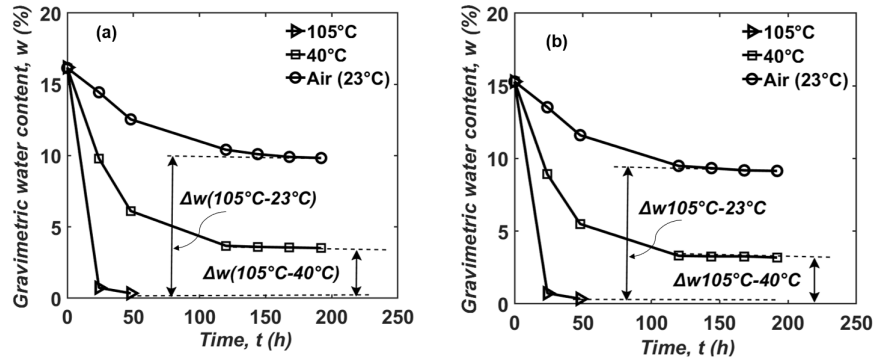


Figure 3: Moisture content variation over time at different drying temperatures (a) ARG1;
 (b) ARG2.

After drying, the materials are separated into several parts, each of which
 is wetted and mixed to a certain water content that corresponds to a targeted
 degree of saturation for the test. The individual parts are then placed in plastic
 155 bags and stored in a styrofoam box for 24 hours to homogenize the water content
 within the material. Cylindrical soil specimens were prepared with a diameter
 of 59mm and a height of 50mm . The soil specimens were divided into two parts.
 Each part is statically compacted in a PVC tube with an internal diameter of
 59mm and a height of 25mm , and at a speed of $2\text{mm}/\text{min}$. The use of PVC is
 160 a technique already used by authors such as [27].

	%MPO	ρ_d (t/m^3)	e
ARG1	95	1.54	0.75
	87	1.43	0.89
	80	1.33	1.03
	75	1.24	1.18
ARG2	95	1.59	0.70
	80	1.33	1.04
	70	1.18	1.29

ρ_d : dry density, %MPO: percent of Modified Proctor Optimum, e : void ratio

Table 2: Initial physical characteristics of specimens used for water retention curve tests

Three layers of filter paper were placed between the two parts to form the specimen. A layer of adhesive tape was placed at the junction of the two parts of the specimen to reinforce the seal at this point. The completed specimens were wrapped in a double layer of plastic film before being placed in glass jars and stored in the styrofoam box for an equilibrium period of four weeks. The procedure is illustrated in Figure 4. The procedure was then repeated to obtain the water retention curves corresponding to each of the targeted dry densities.



Figure 4: Test procedure to determine water retention curves.

After the equilibrium period, the central filter papers were weighed along with the pairs of soil samples to determine the wet masses of the filter papers and those of the soil samples. After drying in an oven at $105^{\circ}C$ for 24 hours, the filter papers and soil samples were weighed again to determine their dry masses. The suction values of the filter paper are determined from the calibration curve

as a function of its moisture content values. One deduces that of the soil. The calibration curve equation is given, for Whatman No. 42 filter paper, by the
 175 equation (Eq. 1) [29]. For these tests, only matric suction was determined.

$$\psi = \begin{cases} 10^{5.327-0.0779.w} & \text{if } w \leq 45.3\% \\ 10^{2.412-0.0135.w} & \text{if } w > 45.3\% . \end{cases} \quad (1)$$

Where w is the gravimetric water content (%) and ψ is the matrix suction (kPa).

2.2.2. Shrinkage test

Shrinkages curves are useful to estimate suction variation and volume variation during drying. Drying and wetting paths are studied to better appreciate
 180 the volumetric behavior of the soil. They have been the subject of several studies, including those in [30]. Drying and wetting test results are generally given as a function of moisture content, saturation degree, void ratio and suction. Drying and wetting curves can be obtained for initially compacted or
 185 consolidated samples and for intact or reworked soil samples.

We carried out shrinkage tests to evaluate the volume behavior of the materials studied. These tests consisted in measuring their volume and mass variation after drying the initially saturated cylindrical soil specimens ($\phi = 59mm$ and $h = 25mm$). The specimens were also prepared by static compaction. The
 190 material chosen for this test was sized to $2mm$.

3. Results and discussion

3.1. Water retention curves

The water retention curves obtained in the plane $(\psi - S_r)$, are shown in Figure 5 for the two materials studied. The results show that the curves translate
 195 from left to right as the initial dry density increases. This shows the influence of the initial compacity of the soil on suction within the material. The higher the initial compacity, the greater the suction within the material. It can also be seen

that after reaching the air entry value, the soil starts to desaturate. Moreover it appears that the air entry value increases with the initial dry density.

200 The water retention curves in the plane $(\psi - S_r)$ were fitted with the [20] model given by equation (Eq. 2) for the case where the suction within the material is greater than the air entry value. The adjustment with the [20] model was applied by considering a single slope since the slopes of the curves in the plane $(\psi - S_r)$ are close for each material, regardless of the initial dry density.
 205 The air entry values for this model were also recorded. The parameters used to fit the retention curves obtained with the [20] model are given in Table 3.

$$S_r = \frac{w(\psi)}{w_s} = \left(\frac{\psi_{aev}}{\psi} \right)^\lambda . \quad (2)$$

With w_s the gravimetric water content at saturation (g/g), $w(\psi)$ is the gravimetric water content as a function of the suction ψ (with w in g/g and ψ in kPa), ψ_{aev} is the air entry value (kPa), S_r is the saturation degree (-) and
 210 λ is the slope of the curve.

The water retention curves obtained in the plane $(\psi - w)$ are shown in Figure 6. It is seen that the effect of dry density is limited for high suction values. After a certain suction value, the curves get closer together. This is consistent with the literature [15]. In our case, this observation is most evident
 215 in the case of ARG2 clay where all the curves come together when suction reaches $1000kPa$. On the other hand, it can be observed that soils with high dry densities have lower saturation water contents due to the fact that for these soils the void volume is smaller and it takes a small volume of water to be saturated. [31] (cited in [32]) gave a range of air entry values as an indication
 220 for soils, i.e. 30 to $800kPa$ for silts and 1000 to $4500kPa$ for clays. In our case, the range of air entry values obtained for dry densities higher than $1.40t/m^3$ (87% of MPO) are consistent with the values given by [31] for clays.

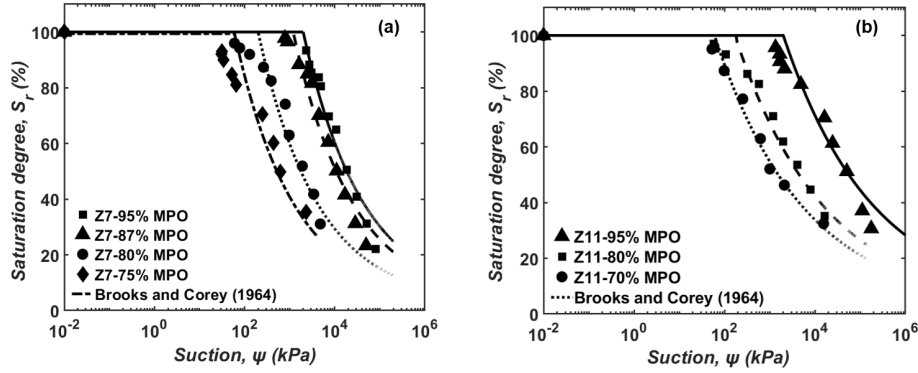


Figure 5: Water retention curve in the plane $\psi - S_r$ (a) ARG1; (b) ARG2.

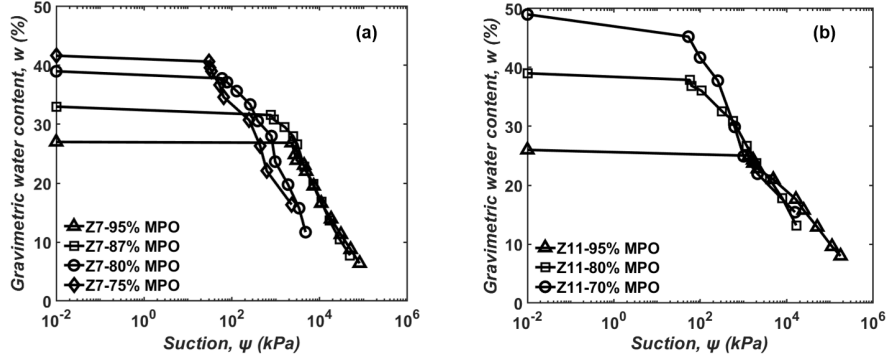


Figure 6: Water retention curve in the plane $\psi - w$ (a) ARG1; (b) ARG2.

3.2. Shrinkage test

Soil samples with two different initial void ratios were prepared. For ARG1 and ARG2, figure 7 shows that whatever the initial void ratio, the drainage path is the same in the plane $(w - e)$. The soil goes through a stabilization stage corresponding to a void ratio at the shrinkage limit ($w_{sL} = 19\%$, $e_s = 0.53$ for ARG1 and $w_{sL} = 16\%$, $e_s = 0.50$ for ARG2).

The void ratio variation between the wet and dry state shows the high sensitivity to soil suction. It is therefore important to determine the drying curves in the planes taking the variation in this parameter into account.

	%MPO	ρ_d (t/m^3)	e	λ	ψ_{aev} (kPa)
ARG1	95	1.54	0.75	0.33	2000
	87	1.43	0.89	0.33	1200
	80	1.33	1.03	0.33	200
	75	1.24	1.18	0.33	60
ARG2	95	1.59	0.70	0.22	2000
	80	1.33	1.04	0.22	170
	70	1.18	1.29	0.22	60

ρ_d : dry density, %MPO: percent of modified Proctor optimum, e : void ratio

Table 3: Parameters used to fit the retention curves obtained with the [20] model.

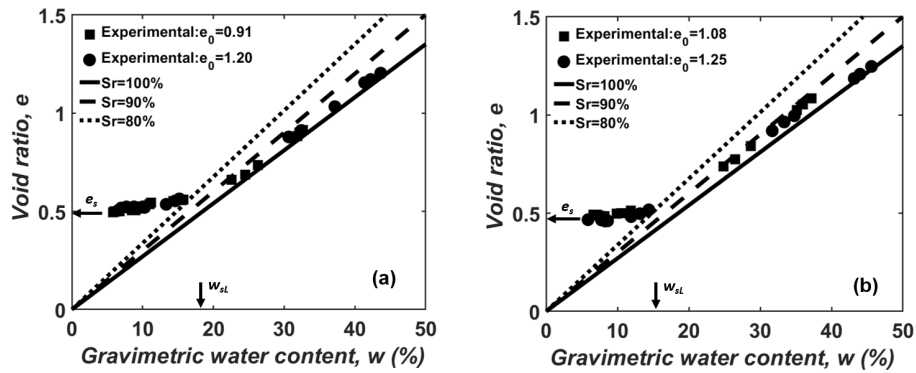


Figure 7: Shrinkage curves $e - w$, (a) ARG1, (b) ARG2.

3.3. Estimation of soil suction

3.3.1. Determination of a bi-linear relationship

For the shrinkage tests, we did not apply a suction measurement method, this is why it was necessary to use a relationship that will enable suction to be estimated as a function of void ratio and saturation degree. Apart from suction, the values for water content, degree of saturation and void ratio are those measured during the drying tests.

Based on the experimental results of SWRCs, it is possible to establish the
 240 relationship between air entry value and void ratio. In general, the air entry
 value decreases significantly as the void ratio increases. Then for a given value of
 the void ratio, the air entry value goes into a stabilization stage with a negligible
 value. [33] have demonstrated this trend by studying the effects of the initial
 void ratio on the water retention curves of a silty clay. They noted that the
 245 higher the initial void ratio (large pore volume), the lower the air entry value.
 Therefore, they correlated these two parameters by a power function (Eq. 3).
 The power model between the void ratio and the air entry value is shown in
 Figure 8.

[9] studied the physical mechanisms that govern the soil-water retention
 250 properties of deformable soils. They showed that air entry value is a function
 of soil skeleton volume information and that the two parameters can be linked
 by the bi-linear approximation model proposed by [34]. This bi-linear model is
 defined by two straight lines (Figure 9). With a straight line equation for the
 first stage given by (Eq. 4), where π_H is a material parameter, e the void ratio
 255 and $\psi_{aev_{ref}}$ the reference air entry value. The variation in the air entry value
 occurs during this first stage. But for the equation of the first straight line to
 be valid, a specific value of the void ratio (e_t) must be defined to ensure that
 the minimum air entry value will be negligible and will not become negative.
 During the second stage, the evolution of the air entry value remains constant
 260 whatever the value of the void ratio.

$$\psi_{aev}(e) = A.e^B \quad \text{with } B < 0. \quad (3)$$

And

$$\psi_{aev}(e) = \pi_H \cdot \frac{\Delta e}{1 + e_0} + \psi_{aev_{ref}} \quad \text{for } e < e_t. \quad (4)$$

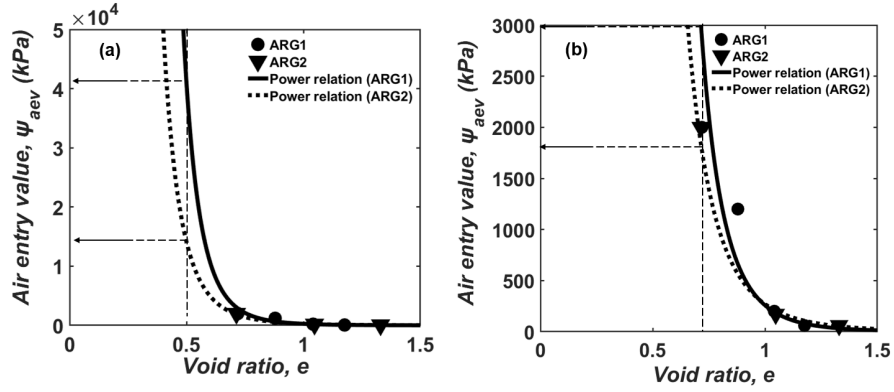


Figure 8: Power relation $e - \psi_{aev}$, (a) extended scale, (b) close scale.

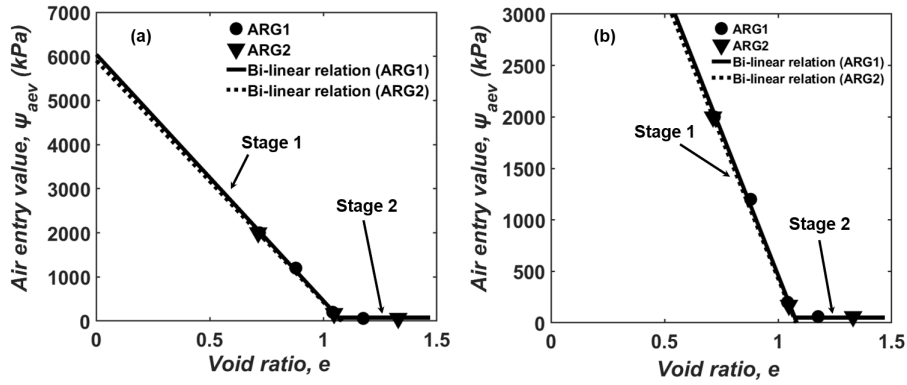


Figure 9: Bi-linear relation $e - \psi_{aev}$, (a) extended scale, (b) close scale.

[9] showed that the bi-linear approximation model of [34] can produce a good estimation of the air entry value. Since the air entry value is influenced by the initial void ratio, it is possible to establish a relationship between these two parameters and to reformulate the [34] model as presented by equation (Eq. 5) where A is a material parameter and B is the reference air entry value. This equation is valid for the first stage of the relationship between void ratio and air entry value. After this stage, the air entry value remains constant.

$$\psi_{aev}(e) = \begin{cases} A.e + B & \text{for } e \leq e_t \\ A.e_t + B & \text{for } e > e_t \end{cases} \quad (5)$$

For ARG1 and ARG2, the bi-linear model was calibrated for specific void ratios of 1.083 and 1.079 respectively for the two soils from which the air entry value becomes minimal and enters a stabilization stage. The power model can lead to an overestimation of the air entry value if the void ratio is below 0.7. An example is shown in Figure 9 where we can see that for a void ratio between 0.7 and 0.5, suction values can move from 2000 *kPa* to 4×10^4 *kPa*. For this reason, the bi-linear model is preferred. The parameters of the two equations are given in Table 4.

Soil	ARG1		ARG2	
	Power	Bi-linear	Power	Bi-linear
<i>A</i>	258.0	-5.6×10^3	270.1	-5.5×10^3
<i>B</i>	-7.3	6.0×10^3	-5.7	5.9×10^3
R^2	0.93	1.00	0.99	1.00

Table 4: Parameters of the two models for the estimation of the air entry value as a function of the void ratio

Thanks to the bi-linear relationship and the [20] model, the suction can be expressed as a function of the void ratio and the saturation degree by (Eq. 6). The relationship between void ratio and suction enabled soil volumetric deformation during shrinkage to be estimated.

$$\psi(e) = \begin{cases} (A.e + B).S_r^{-1/\lambda} & \text{for } e \leq e_t \\ (A.e_t + B).S_r^{-1/\lambda} & \text{for } e > e_t \end{cases} \quad (6)$$

3.3.2. Application of the bi-linear relationship

Figures 11 to 13 show the variation of water content, void ratio and saturation degree as a function of suction. Several authors such as [9] have shown that in the plane $[\log(\psi) - w]$, the effect of the initial void ratio becomes negligible on SWRCs during soil desaturation. This is due to the existence of a point from which the SWRCs converge (Figure 10). For ARG1 and ARG2, this is not clearly evident. The results show that regardless of the initial void ratio, the drainage paths overlap. The same trend is observed in the planes $[\log(\psi) - S_r]$ and $[\log(\psi) - e]$. The bi-linear relationship does not show the effect of dry density on the SWRCs for ARG1 and ARG2.

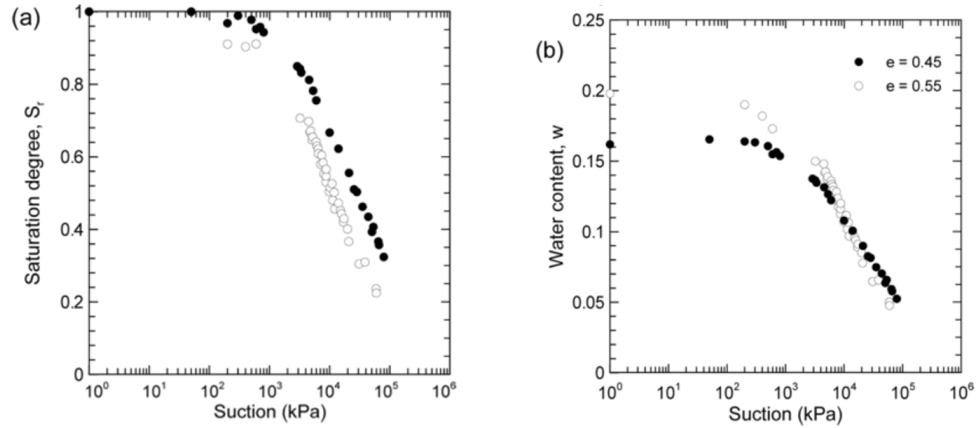


Figure 10: Soil water retention curves [9].

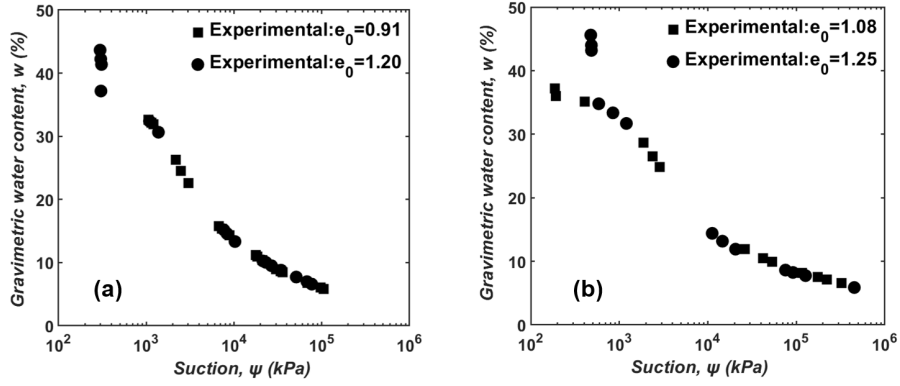


Figure 11: Soil water retention curves $w - \psi_{aev}$, (a) ARG1, (b) ARG2.

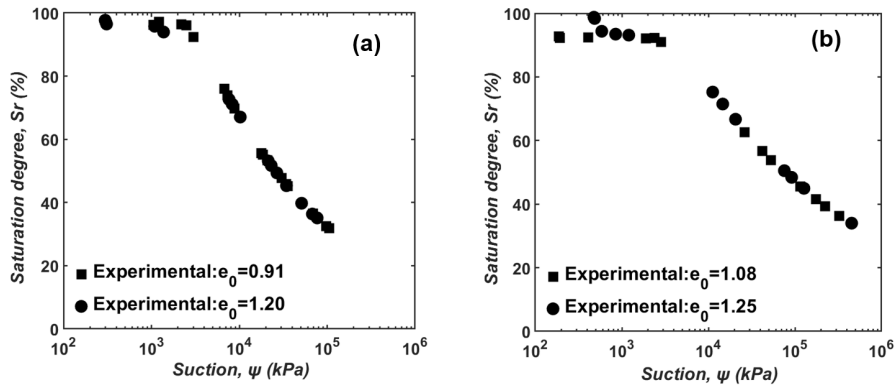


Figure 12: Soil water retention curves $S_r - \psi_{aev}$, (a) ARG1, (b) ARG2.

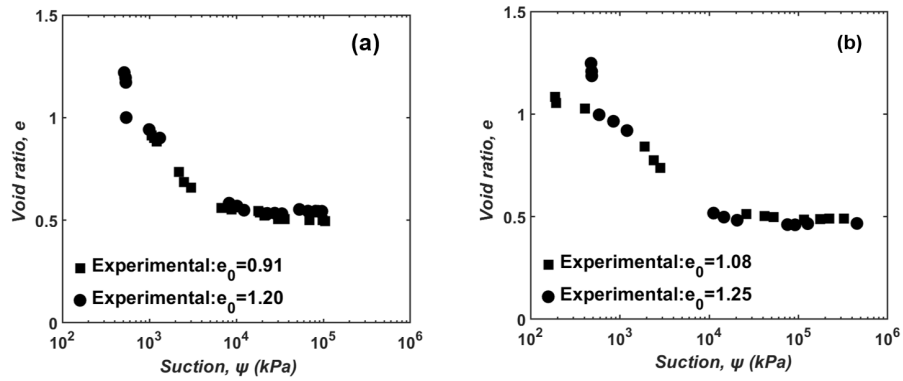


Figure 13: Shrinkage curves $e - \psi_{aev}$, (a) ARG1, (b) ARG2.

The results show that the estimated suction values are reasonable. These tests highlight the sensitivity to water variations of the soil studied since the suction values can exceed $10MPa$. The soils studied show significant volumetric deformations (ε_v), more than 30% for the two materials studied. Volumetric deformations are computed by the relation given by the equation (Eq. 7), where ε_1 and ε_3 are respectively the axial and lateral deformations. In addition, the deviation between the initial and final void ratio values is in the 50% and 60% range. These deviations show that the material can lose more than half of its initial volume during drying. The initial and final measured characteristics of the materials are given in Table 5.

$$\varepsilon_v = \varepsilon_1 + 2.\varepsilon_3 . \quad (7)$$

	Initial state			Final state			ε_v (%)
	e_i	w_i (%)	S_{r_i} (%)	e_f	w_f (%)	S_{r_f} (%)	
ARG1	1.22	43.6	96.4	0.53	5.1	26.0	35
	0.91	32.6	96.2	0.49	5.6	30.3	24
ARG2	1.08	37.2	92.8	0.49	4.2	23.0	32
	1.25	45.6	98.8	0.48	2.8	16.0	39

Table 5: Initial and final characteristics measured during the drying test for ARG1 and ARG2

3.4. Application of the MK model to predict soil water retention curves

Because of the difficulties that can be encountered in carrying out laboratory tests (high cost, time consuming and possible lack of suitable equipment), it may be useful to use a model to estimate water retention curves. The Modified Kovács model (MK model) is one of the water retention curve prediction models that give satisfactory results ([35]; [8]). This model is based on the principle that soil suction results from the simultaneous effects of capillary forces and adhesion forces acting at the soil grain surface to induce suction. The MK model is suitable for granular soils. [8] proposed a version of the MK model extended to be applied to deformable soils, called the MK_d model. It is assumed that the soil is isotropic and homogeneous, under a drainage path for the MK model and the MK_d model. But only in the case of the MK model, are the effects of internal microstructure, anisotropy and volume variations neglected. In the remainder of this work, we analyze how practical the modified Kovács model is with respect to the tropical residual soils studied.

The materials studied are fine, compressible soils. The SWRCs were determined on the one hand with the filter paper method by preparing soil samples with constant void ratios and on the other hand by means of drying tests during which the volume deformation of the soil induces the variation of the void ratio. Thus the SWRCs at a constant void ratio are estimated by considering the material as a non-deformable soil in the MK model formulation. For drying tests, the MK_d model will be used to estimate the SWRCs.

The MK model is based on the consideration that the degree of saturation is the sum of the adhesion component (S_a) and the capillary component (S_c) (Figure 14). According to [35], in expressing the degree of saturation, the truncated value of the adhesion component (S_a^*) is taken into account instead of its own value (S_a). This is to prevent the value of S_a from exceeding unity when suction is weak ($0 \leq S_a^* \leq 1$). The truncated value of the adhesion component (S_a^*) is expressed in terms of Macauley's brackets $\langle y \rangle$ ($\langle y \rangle = 0.5(y + |y|)$); for $S_a \geq 1$, $S_a^* = 1$ and for $S_a < 1$, $S_a^* = S_a$. In case of non-deformable soils, the values of S_c and S_a are given by equation (Eq. 8) and (Eq. 9) as a function of

the initial void ratio (e_0). The expression of the truncated value of the adhesion component is given by equation (Eq. 10) and the degree of saturation by equation (Eq. 11).

$$S_c = 1 - \left[\left(\frac{h_{co,P}}{\psi} \right)^2 + 1 \right]^m \cdot \exp \left(-m \left(\frac{h_{co,P}}{\psi} \right)^2 \right). \quad (8)$$

$$S_a = a_c \cdot C_\psi \cdot \frac{\left(\frac{h_{co,P}}{\psi_n} \right)^{2/3}}{e_0^{1/3} \cdot \left(\frac{\psi}{\psi_n} \right)^{1/6}}. \quad (9)$$

$$S_a^* = 1 - \langle 1 - S_a \rangle. \quad (10)$$

$$S_r = S_c + S_a^*(1 - S_c). \quad (11)$$

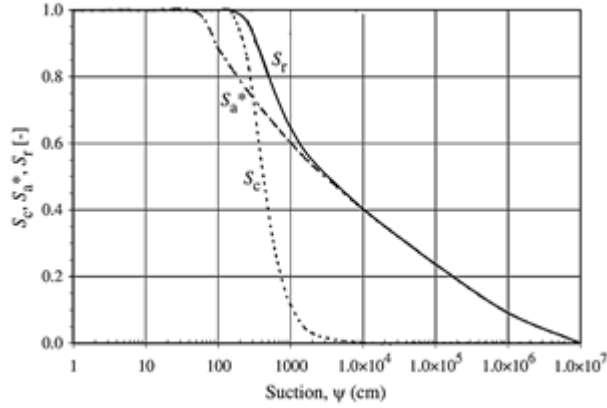


Figure 14: Illustration of the degree of saturation related to capillary and adhesion components when determining the total saturation degree – case of a cohesive soil [35].

335 With ψ_n a normalized parameter is introduced for unit consistencies ($\psi_n \approx 10^{-3}$ atmosphere). C_ψ is given as a function of the suction ψ , the residual suction ψ_r and the suction ψ_0 by equation (Eq. 12) (ψ_0 is the suction corresponding approximatively to complete dryness). The equivalent capillary height $h_{co,P}$ and the residual suction ψ_r are given by equations (Eq. 13) and (Eq. 14).

$$C_\psi = 1 - \frac{\ln(1 + \psi/\psi_r)}{\ln(1 + \psi_0/\psi_r)} . \quad (12)$$

$$h_{co,P} = \frac{0.15 \cdot \rho_s}{e_0} \cdot w_L^{1.45} . \quad (13)$$

340 And

$$\psi_r = 0.86 \left(\frac{0.15 \cdot \rho_s}{e_0} \right)^{1.2} \cdot w_L^{1.74} . \quad (14)$$

The parameter a_c is the adhesion coefficient and the parameter m is related to the pore size. According to [35], when using the MK model to predict SWRCs for non-deformable soils, these two parameters are considered constant such that $m = 3 \times 10^{-5}$ and $a_c = 7 \times 10^{-4}$.

345 [8] proposes instead to calculate the parameter m , for the case of deformable soils, as a function of the initial void ratio (e_0) and the minimum void ratio, at the shrinkage limit (e_s) as given by equation (Eq. 15). Since the void ratio varies during drying, the formulations of the MK model given earlier should be used considering the void ratio given by equation Eq. 16.

$$m = 3 \times 10^{-5} + 0.04 \cdot \left(\frac{e_0 - e_s}{e_0} \right)^{3.3} . \quad (15)$$

$$e(\psi) = e_s + \frac{e_0 - e_s}{1 + \alpha \left(\frac{\psi}{\psi_n} \right)^\beta} . \quad (16)$$

350 With α and β two parameters related to the void ratio (void ratio to shrinkage limit (e_s), initial void ratio (e_0) and void ratio to liquid limit (e_L)) are given below.

$$\alpha = 8.7 \times 10^{-3} \left(\frac{e_0}{e_L} \right)^{3.09} . \quad (17)$$

$$\beta = 0.63 \left(\frac{e_L}{e_0 - e_s} \right)^{0.22} . \quad (18)$$

To obtain the void ratio to shrinkage limit (e_s), [8] propose estimating e_s according to the shrinkage limit w_{sL} as given below.

$$w_{sL} = LL - 1.22.PI . \quad (19)$$

355 And

$$e_s = \frac{G_s \cdot w_{sL}}{100} . \quad (20)$$

3.4.1. Application for SWCs with constant void ratio

Figure 15 shows the comparison between the predicted SWRCs for non-deformable soils and the experimentally determined SWRCs considering a constant void ratio by means of the filter paper method. Overall, the predicted
 360 SWRCs show a good shape, but the air entry value is underestimated for high dry densities, especially for dry density between 80% and 95% of the MPO (Table 9). The model parameters are given in Table 6 and the material parameters are listed in Table 7. Table 8 shows the values of the coefficients of determination between the predicted and experimental saturation degree values. A better
 365 estimate is found for the ARG2 clay with R^2 values of 0.90 and 0.96.

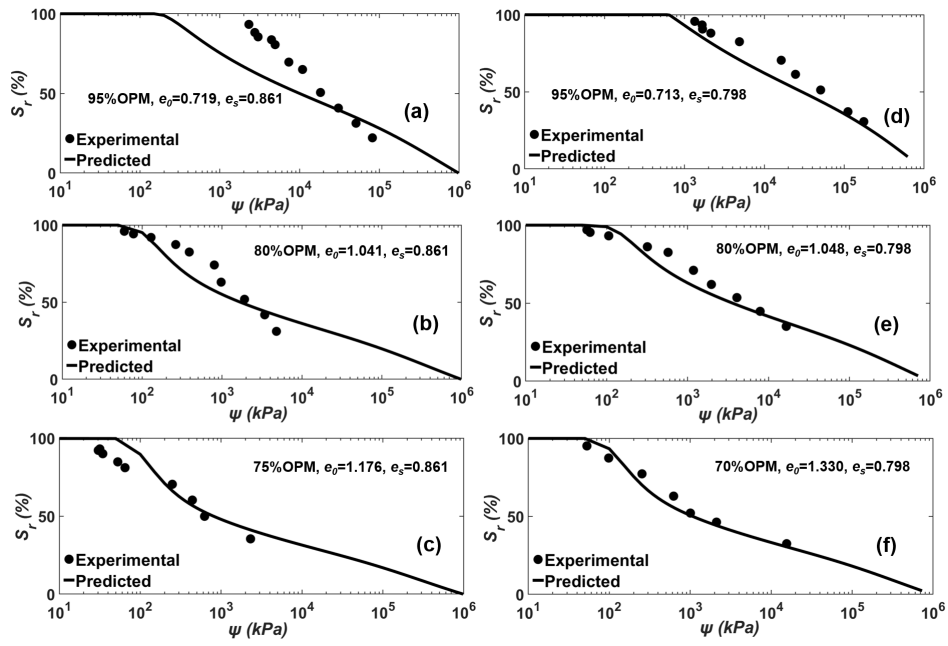


Figure 15: Estimation of water retention curves with the modified Kovács model. (a), (b) and (c) for ARG1 and (d), (e) and (f) for ARG2.

	%MPO	ϵ_0	ψ_r (kPa)	ψ_n (kPa)	ψ_0 (kPa)	$h_{co,P}$ (kPa)	a_c	m
ARG1	95	0.75	3.21×10^5	9.80×10^{-2}	9.80×10^5	2.99×10^4	7.0×10^{-4}	3.0×10^{-5}
	80	1.03	2.19×10^5	9.80×10^{-2}	9.80×10^5	2.17×10^4	7.0×10^{-4}	3.0×10^{-5}
	75	1.18	1.86×10^5	9.80×10^{-2}	9.80×10^5	1.90×10^4	7.0×10^{-4}	3.0×10^{-5}
ARG2	95	0.70	4.52×10^5	9.80×10^{-2}	9.80×10^5	3.98×10^4	7.0×10^{-4}	3.0×10^{-5}
	80	1.04	2.80×10^5	9.80×10^{-2}	9.80×10^5	2.66×10^4	7.0×10^{-4}	3.0×10^{-5}
	70	1.29	2.15×10^5	9.80×10^{-2}	9.80×10^5	2.14×10^4	7.0×10^{-4}	3.0×10^{-5}

Table 6: Selected characteristics for the MK model and the MK_d model

	%MPO	e_0	C_{80} (%)	PI (%)	LL (%)
ARG1	95	0.75			
	80	1.03	92.65	38.50	78.90
	75	1.18			
ARG2	95	0.70			
	80	1.04	81.06	50.60	91.30
	70	1.29			

%MPO: Percent of modified Proctor optimum, e_0 : Initial void ratio, C_{80} : Percent fines, PI : Plasticity index, LL : Liquid limit

Table 7: Parameters of the materials

	%MPO	e_0	R^2
ARG1	95	0.75	0.47
	80	1.03	0.84
	75	1.18	0.81
ARG2	95	0.70	0.89
	80	1.04	0.92
	70	1.29	0.96

%MPO: percent of modified Proctor optimum, e_0 : initial void ratio

Table 8: Verification of the MK model and the MK_d model

	%MPO	ρ_d (t/m^3)	ψ_{aev} (kPa) [35]	ψ_{aev} (kPa) Experimental
ARG1	95	1.54	200	2000
	80	1.33	80	200
	75	1.24	60	60
ARG2	95	1.59	600	2000
	80	1.33	100	170
	70	1.18	70	60

%MPO: percent of modified Proctor optimum, e_0 : initial void ratio

Table 9: Comparison between air entry values determined by the MK model and by experimental results

The results show that it is possible to have a good estimation of SWRCs with a constant void ratio with the MK model but it may give air entry values differing from the true values.

3.4.2. Application for SWCs with void ratio variation

370 During the drying of the soil, there is a volume change associated with the suction change. The MK_d model enables the variation in the void ratio during drying to be taken into account to estimate the SWRCs. To apply the MK_d model, the relationship between water content at the shrinkage limit (w_{sL}) and liquid limit (LL) was determined for ARG1 and ARG2. The new formulation
375 is given by equation (Eq. 21).

$$w_{sL} = LL - 1.51.PI . \quad (21)$$

Figure 16 shows the comparison between the curves predicted with the MK_d model and the SWRCs determined during the drying tests. The results obtained are satisfactory and show a good applicability of the MK_d model in the plane $[\log(\psi) - S_r]$. However, in the $[\log(\psi) - e]$ plane, there is an underestimation of
380 the void ratio values. This is shown in Figure 17.

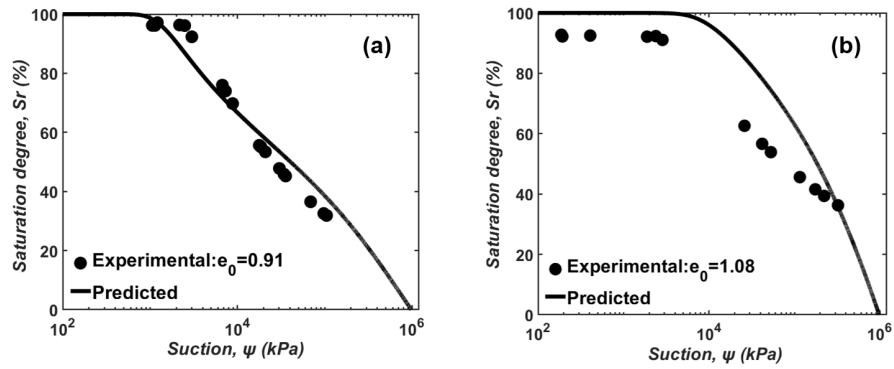


Figure 16: Prediction of water retention curve with void ratio variation with the MK_d model. (a) ARG1, (b) ARG2.

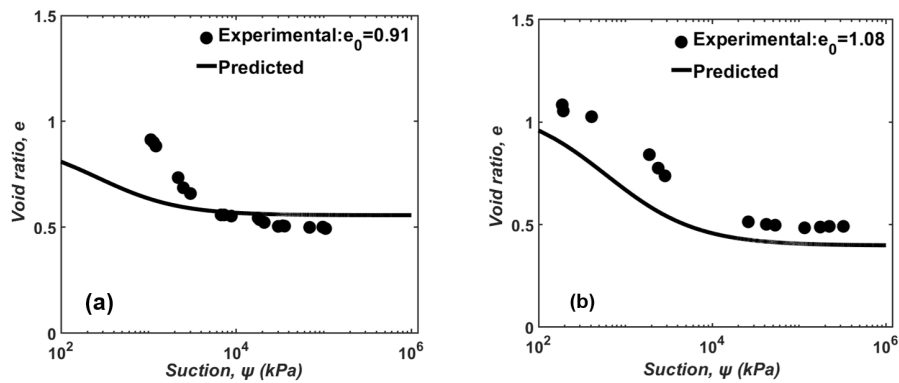


Figure 17: Prediction of void ratio variation with the MK_d model. (a) ARG1, (b) ARG2.

The results show that the MK_d model provides a good estimate of the SWRCs when the void ratio varies with suction.

4. Conclusion

This paper deals with some aspects of the unsaturated behavior of two residual tropical soils present in the interior Gabon basin. SWRCs for various initial void ratios have been determined by using the filter paper method. The results have shown that there is a point of convergence of the SWRCs in the (ψ, w) plane at which the influence of the initial void ratio or the initial dry density becomes negligible. This trend and the air entry values for the soils studied are consistent with the literature.

The SWRCs with a constant void ratio were used to redefine the approximate bi-linear model proposed by [34] that enables the air entry value to be expressed as a function of void ratio. This relationship was subsequently used to estimate suction as a function of void ratio and saturation degree during soil shrinkage. The bi-linear relationship was preferred to the power relationship because for the materials studied, the latter relationship can lead to the suction being overestimated if the void ratio is less than 0.7.

The application of the modified Kovács model to predict SWRCs with a constant void ratio provides SWRCs with a good shape, but for high dry densities the air entry value is underestimated. The SWRCs obtained with the modified Kovács model with a variable void ratio provides a good estimate of the SWRCs but a calibration of the relationship between the void ratio at the shrinkage limit and the soil properties is necessary.

The applicability of the bi-linear model and the prediction model (MK model) is verified for this type of soil.

For the shrinkage tests, no suction measurement method was used. We deduced suction values from the relationship proposed by [20] and the bi-linear relationship between air entry value and void ratio. For the materials studied, the bi-linear relationship does not enable the effect of initial dry density on SWRCs to be shown.

The large volume variations measured during the drying tests showed the particular character of this type of soil which does not enable them to be used

as subgrade materials. Indeed, such a material can show shrinkage/swelling phenomena that cause soil instability.

415 **Data Availability Statement**

The data that support the findings of this study are available from the corresponding author, upon reasonable request.

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