

Article

Experiment and Modelling Characterisation of Clay Effect on Soil Water Retention Capacity

Yu Wang ^{1,*} , Amjad H. Albayati ² , Xingtao Fu ³, Mhd Naaman Al Braway ¹ , Vincent Uzomah ¹
and Miklas Scholz ⁴ 

¹ School of Science, Engineering & Environment, University of Salford, Manchester M5 4WT, UK; m.n.albraway@edu.salford.ac.uk (M.N.A.B.); v.uzomah@salford.ac.uk (V.U.)

² Department of Civil Engineering, University of Baghdad, Baghdad 10071, Iraq; a.khalil@uobaghdad.edu.iq

³ College of Water Conservancy Science and Engineering, Taiyuan University of Technology, Taiyuan 030024, China; fuxingtao@tyut.edu.cn

⁴ Department of Civil Engineering Science, School of Civil Engineering, and the Built Environment, Faculty of Engineering and the Built Environment, University of Johannesburg, Auckland Park, Johannesburg 2092, South Africa; mscholz@uj.ac.za

* Correspondence: y.wang@salford.ac.uk

Abstract

This paper reports a research work on assessing clay content effect on the water retention capacity of clayey sandy soils. At first, experimental tests were conducted to measure the soil water retention curves (SWRCs) of clayey sandy soils. A total of four different soil samples, which have clay content of 0, 15, 30 and 50%, respectively, by total soil sample weight, were measured. Secondly, a revision of a physical–chemical (PC) analytical model previously proposed has been reviewed and adopted to represent the SWRC measurements and compared for its predictive performance against the classic van Genuchten model and the original PC model. The experimental results demonstrated that clay content has a significant influence on soil water retention capacity, showing that a positive correlation generally exists between them. The modelling results showed that the revised analytical model not only produced a good representation for the soil water retention curves over whole range of soil water content, particularly at low water content side, but also provided advanced insight into the fundamental physics underlying soil water retention mechanisms. The analysis of its parametric data highlights the functions of the involved physics and their roles shaping the SWRCs, which intrinsically relate to specific surface area, pore size distribution, and particle size and shape. At last, the model was used to describe the pore size distribution from a revised concept against conventional approach. However, the revised concept and approach needs further wide verification and is open for discussion.

Keywords: clayey sandy soil; soil water retention capacity; soil water retention curve modelling



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1. Introduction

Clayey sandy soils, due to their general existence and broad variation in composition, have received increasing research interest in agricultural engineering [1–3], hydrology [4], soil physics [5], and wide multidisciplinary problems [6,7]. As the features of clayey sandy soils, including fertility, hydrological function and mechanical stability [8–11], are highly influenced by the existence of water inside, understanding the clay effect on the water retention capacity and corresponding influence on wide physical properties has fundamental research interest [12,13].

Soil water retention capacity is primarily governed by soil texture and pore network characteristics [14]. The associated water retention behaviour is controlled by molecular interactions occurring at particle surfaces together with derived capillary condensation within pore spaces [15,16]. Soil water retention behaviour is commonly characterised using the soil water retention curves (SWRCs), a constitutive relationship between soil water content and matric suction. In addition, the SWRCs are widely employed to predict hydraulic conductivity and diffusivity because these hydraulic properties are intrinsically connected through pore-size distribution and particle-scale characteristics [17,18].

Modelling of SWRCs has been given sustaining research attention over past decades [19–22]. Over time, numerous conceptive approaches and mathematical models have been proposed and developed to characterise SWRCs in general [23]. Among them, the formula proposed by van Genuchten [24] remains the most popular one to date; since then, a number of revised versions have also been proposed for improvement for predictive performance [25–27]. Meanwhile, over the past couple of decades, researchers tried to interpret soil water retention behaviour by incorporating both capillarity and surface adsorption mechanisms. On the theoretical framework of capillarity, soil matric suction is equivalent to the pore water potential energy derived from the water surface tension along the air–water menisci formed at the bulk waterfronts at pore scale and evaluated using the Laplace’s equation related to the meniscus radius [28]. Seeing that water generally starts accumulating at the angular corners at pore scale irrespective of pore size, Tuller et al. [29] formulated soil matric suction to have two independent components. The first component is attributed to capillarity characterised by the surface tension along air–water menisci, which is evaluated using the classical Laplace equation. The second component accounts for the adsorption forces associated with the thin water film coating on the surfaces of unfilled pores, which is called the disjoining pressure related to the water film thickness [30]. The approach was thereafter implemented through varied specific microscopic pore geometric models [29]. Subsequent studies further extended the pore-scale water retention modelling approach, adopting different pore geometries and assumptions [31–36]. As such pore-scale models rely on simplified mean-field assumptions for capillary condensation in slit-shaped pores [30], they may not adequately represent realistic pore systems. Furthermore, as the water film is strongly related to soil particle size, particle surface curvature, and the thickness of itself, a flat slit configuration would miss the fact that convex particle curvature may reduce the net adsorption contribution because of tensile stresses acting along curved water film surfaces. On the other hand, using a specific pore geometric shape to represent actual soil pore structures overly simplifies the complexity of the pore network system. In addition, suction estimated at the pore scale does not directly correspond to bulk-scale soil suction. The latter stands for a volume average over all individual pores [37]. To upscale from pore level to bulk material level, Wang et al. [38] proposed a physical–chemical model for SWRCs, which also starts from the concept that surface water film and condensed bulk pore water coexist in unsaturated pore network [38,39], but the soil matric suction is evaluated by volume average theorem.

In addition to the pore-scale characteristic models for SWRCs, to improve the representation of soil water retention behaviour across the full saturation spectrum ranging from very dry to fully saturated, other methodology and approaches have also been investigated in recent years. The examples include the segment-based modelling techniques [23,40], as well as the integrated sorption–isotherm and capillary models [40]. However, segmental approaches, which divide the soil water retention curve into adsorption-dominated and capillarity-dominated regions, may not adequately capture the simultaneous interaction of surface adsorption and capillary condensation throughout the entire unsaturated range. In addition, combined sorption–isotherm and capillary formulations often involve a relatively

complex mathematical formulation, which might involve in stepwise implementation of curve fitting. Aiming to accurately describe the SWRCs at low water content, recently, Smagin [41,42] introduced a general phenomenological theory to describe the disjoining pressure of water films. In another effort, Wang [43] further developed a previously proposed and developed physical–chemical (PC) model [38,39], introducing a term for the effect of water film at unsaturated states.

This paper at first reports an experimental test measuring the influence of clay content on the SWRCs of clayey sandy soils. The control soil (benchmark) is pure sand, on which three soil samples of different clay contents by sample weight were prepared. Drying soil water retention curves were measured using the evaporation method starting from fully saturated state using a state-of-the-art device, HYPROP-2 [44]. The revised physical–chemical SWRC model [43], referred to as three-phase model in rest of this work, was adopted to represent the SWRC measurements. In comparison, not only do its modelling results demonstrate a better performance than those using the van Genuchten model and the previous form of the physical–chemical (PC) model but its parametric analysis also provides insightful information for the underlying mechanisms aligning with the fundamental physics incorporated in the model. At last, further investigation was performed to explore its potential advanced capacity to provide a pore structural illustration from an aspect different from the conventional approach.

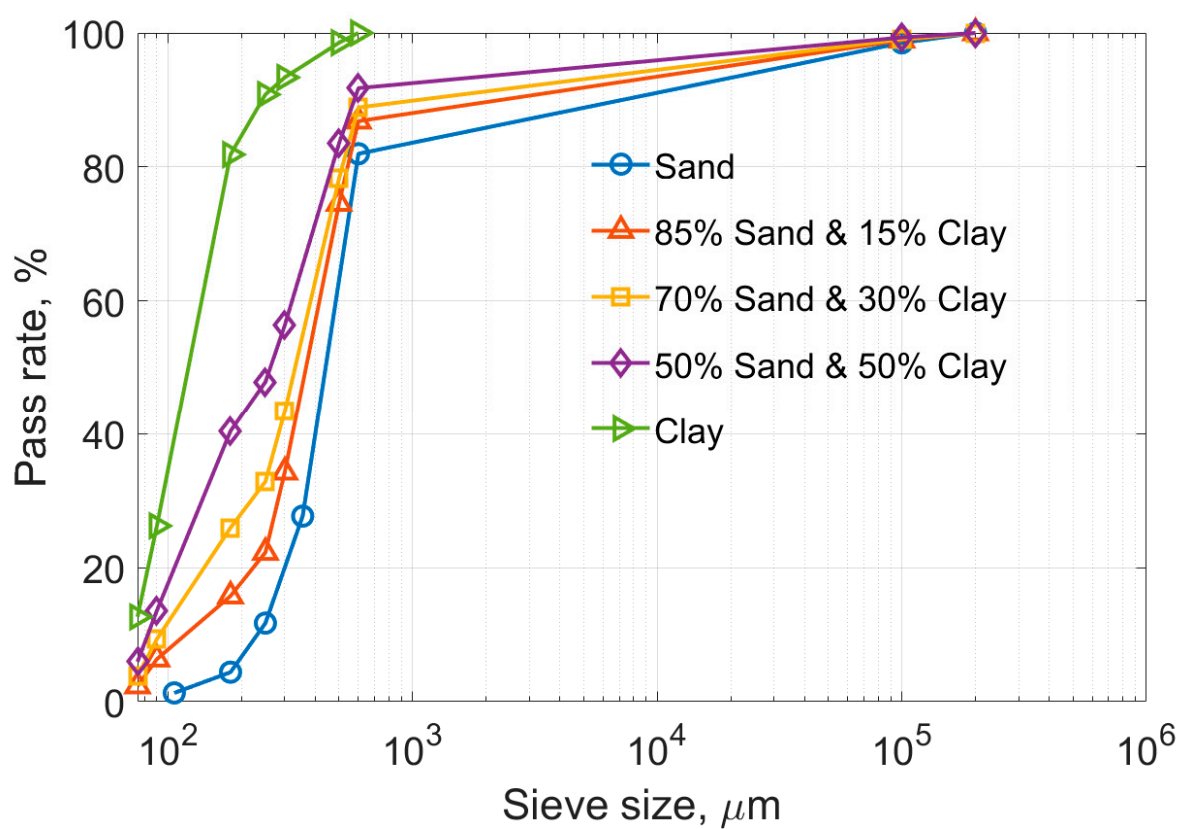
2. Materials and Experiment

The raw materials are yellow sand and Bolour clay, as shown in Figure 1a. Both are for building construction purposes. The control/benchmark soil is a pure sand with particle sizes in the range from 0.06 mm to 2 mm. The clay additive has the maximum particle size about 500 μm . Table 1 lists out the prepared soil samples. Figure 1b shows the particle size distribution of the sand, clay and their mixtures. The particle size distribution of the mixes is calculated in terms of sand to clay proportion.

The state-of-the-art equipment, HYPROP-2, was used to measure the drying SWRC curves [45]. Both sand and clay were dried separately at first in an electrical oven at 110 °C for 24 h to achieve 100% dried. The oven-dried sand and clay then were taken to make four soil mixtures according to the sand to clay weight ratio given in Table 1. The mixtures were made by blending manually. Thereafter, the prepared soil mixes were loaded into the sample ring of HYPROP-2, respectively, for each of the tests. The amount of the loaded soil mix for each test just reaches the level of the full volume capacity of the sample rings, given slight compaction on top with a constant force and times. Thereafter, the soil-loaded HYPROP-2 sample rings were put into glass containers filled with distilled water. The surface of the water within the container was kept at 2/3 of the height of the sample rings. The pressure sensors and the base units of the HYPROP-2 were degassed and set up following the procedure specified in the operation menu. After 24 h, all soil samples bathed in the containers, assumed to have been fully saturated, were taken out and installed on the set-up HYPROP-2 unit to start the tests as shown in Figure 2a. All the tests thereafter were conducted automatically until the HYPROP-2 devices ran out of their measurement range/capacity (Figure 2b). The tests were completed by triplication for each of the mixes except for the mix of 50% sand and 50% clay, for which the data were from the other study conducted before [46]. The measurements of the suction, water content, soil density and porosity were recorded and calculated by the software of the HYPROP-2.



(a) Raw materials

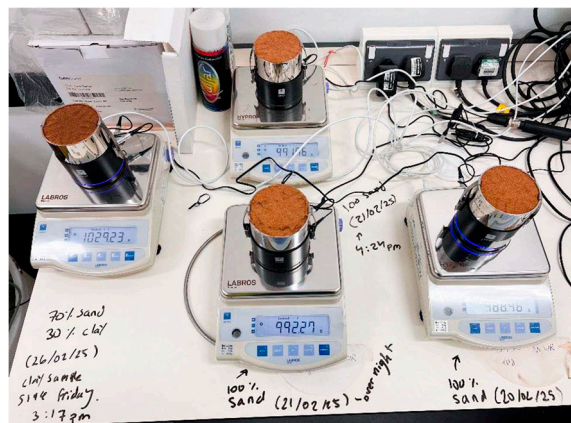
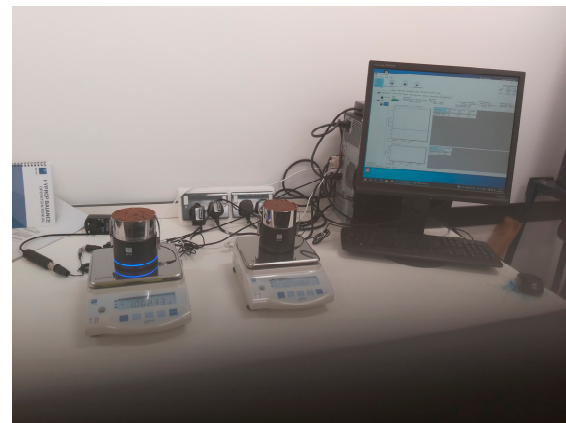


(b) Particle size distribution of the sand, clay and their mixtures

Figure 1. Raw materials and particle size distribution of soils samples.

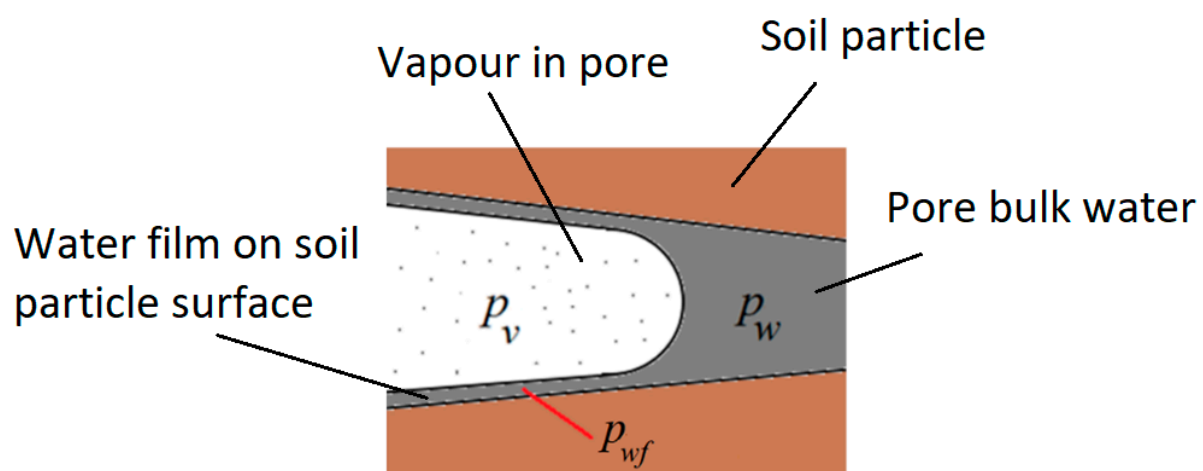
Table 1. The soil samples for the SWRCs test.

Samples	Sand (Wt%)	Clay (Wt%)	Porosity	Density (g/cm ³)	Water Content at Normalising Point (Fully Saturated) (Vol%)
Sand (Control)	100	0	0.40	1.6	34.67
Clayey sand A	85	15	0.44	1.48	34.49
Clayey sand B	70	30	0.40	1.6	37.68
Clayey sand C	50	50	0.32	1.81	41.43

**(a)** Samples on the set-up HYPROP-2 unit**(b)** Automatically recorded test**Figure 2.** SWRC measurement using HYPROP-2.

3. A Novel Three-Phase Model for Soil Water Retention Characteristics

A three-phase model, a revision on a previously proposed and developed physical–chemical (PC) model for static water retention in unsaturated porous media [38,39,46], is adopted. As illustrated in Figure 3, for unsaturated soils, three water phases coexist in pore space; they are the bulk water phase in the filled pore volume (V_{water}); the vapour/air in the empty pore volume (V_{vapour}); and the water film on the empty pore surfaces. The pore water matrix potential is determined by the state of the three phases together, which therefore is expressed in the form of Equation (1) below.

**Figure 3.** The water at pore scale in unsaturated soils.

p_v —pore vapour/air pressure; p_w —pore water pressure; p_{wf} —pore water film pressure

$$\psi_m = P_c + P_s = (\langle p_w \rangle - \langle p_v \rangle) + \langle p_{wf} \rangle \quad (1)$$

where $P_c = (\langle p_w \rangle - \langle p_v \rangle)$ is a component attributed to capillarity or called capillary pressure, which is evaluated by the interfacial meniscus between bulk pore water and the pore vapour; $P_s = \langle p_{wf} \rangle$ is the component attributed to the entire water film on empty pore surfaces, i.e., surfaces of soil particles. The bracket, $\langle \rangle = \frac{1}{V_{REV}} \int_0^{V_{pore}} dV$, is an operator for the volume average of bulk soil. The V_{REV} stands for representative elementary volume of bulk soil, and V_{pore} is the total pore volume in the V_{REV} . The pore-scale pressure of the three phases can be evaluated by the Kelvin equation, Equation (2), below.

$$p_{fi} = p_0 \exp\left(\frac{\overline{\Delta\mu_{fi}}}{RT}\right) \quad (2)$$

where p_{fi} is the average gauge pressure of the fluid phase i on an adsorbent surface (i.e., soil particle surfaces); $\overline{\Delta\mu_{fi}}$ is a local average intrinsic molar chemical potential change of the fluid phase i , which is defined as $\overline{\Delta\mu_{fi}} = \frac{1}{t} \int_0^t \Delta\mu_{fi}(z) dz$, where t is the thickness fluid phase on the adsorptive substrate surface and $\Delta\mu_{fi}(z)$ is the molar molecule potential change of the fluid phase at position z above the substrate surface. R is the gas constant; T is the temperature; and p_0 is a normal pressure of water phase. In unsaturated soils, the volume average pressure for the bulk water phase can be expressed as: $\langle p_w \rangle = \frac{1}{V_{REV}} \int_0^{S_w V_{pore}} p_w dV$, where $S_w = V_{\text{water}}/V_{\text{pore}}$ is the pore water saturation degree. Similarly, the volume average pressure for the coexisting bulk vapour phase can be expressed as: $\langle p_v \rangle = \frac{1}{V_{REV}} \int_0^{(1-S_w)V_{pore}} p_v dV$. Substituting Equation (2) for the p_w and p_v in the volume average formulas, $\langle p_w \rangle$ and $\langle p_v \rangle$, the volume average of the capillary pressure component in Equation (1) can be rewritten in the form of Equation (3) [39].

$$P_c = \lambda \left[\frac{1}{\alpha} (\exp(\alpha S_w) - 1) - \frac{1}{\beta} (\exp(\beta(1 - S_w)) - 1) \right] \quad (3)$$

where λ is a constant relevant to the porosity (V_{pore}/V_{REV}) and the initial water film condition when bulk water starts to accumulate in pore volume due to capillary condensation; α is a constant relevant to the interfacial force between the condensed bulk water phase and the soil particles, while β is a constant relevant to the interfacial force between the vapour phase, the water film and the pore wall surfaces underneath.

To evaluate the water film component $\langle p_{wf} \rangle$ in Equation (1), a t -curve model was adopted here. t -curve is a plot of the statistical thickness of the adsorbate liquid film on the surface of nonporous adsorbents at varied adsorbate vapour pressures [47]. It plays an important role in pore structure analysis and provides an alternative method to estimate the specific surface area of porous media in addition to the BET model [48–51]. De Boer et al. [52] reviewed three empirical models that had been successfully used to represent the measurements of the nitrogen adsorption isotherms of nonporous adsorbents. They are the modified BET model (Equation (4)), the Harkins–Jura model (Equation (5)) and the Frenkel–Halsey–Hill model (Equation (6)). The three models have become useful tools in pore structure analysis [53,54].

$$t = \frac{V}{V_m} = \frac{ck(p/p_0)}{(1 - k(p/p_0))(1 + (c - 1)k(p/p_0))} \quad (4)$$

$$\log(p/p_0) = B - \frac{A}{t^2} \quad (5)$$

$$p/p_0 = \exp\left(\frac{-C}{tr}\right) \quad (6)$$

where t is the statistic water film thickness and p/p_0 is the vapour relative pressure, which decides the intrinsic potential of the water film at the thickness t . Meanwhile the intrinsic potential can be described using the Kelvin equation (Equation (2)). Comparing Equation (2) with Equation (6), we may obtain Equation (7).

$$\frac{\overline{\Delta\mu_{wf}}}{RT} = \frac{-C}{t^r} \quad (7)$$

In unsaturated soils, the $\overline{\Delta\mu_{wf}}$ decides the pressure of the water film on empty pore wall surfaces and t is linked to the pore water saturation degree. Based on the understanding, a power function, Equation (8), is tried here to describe the contribution of the water film on empty pore walls to the matric suction in terms of pore water saturation, S_w .

$$\langle p_{wf} \rangle = \chi(1 - S_w)^\kappa \quad (8)$$

where χ and κ are two constants. Substituting Equations (3) and (8) into Equation (1), the macroscopic water matric potential (or suction) in unsaturated soils can be expressed in the form of Equation (9).

$$\psi_m = \lambda \left[\frac{1}{\alpha} (\exp(\alpha S_w) - 1) - \frac{1}{\beta} (\exp(\beta(1 - S_w)) - 1) \right] + \chi(1 - S_w)^\kappa \quad (9)$$

In the next section, Equation (9) is adopted for curve fitting to represent the SWRC measurements obtained in the preceding experimental tests. All curve fitting, data calculation, and results plots and presentation were performed using the software, MATLAB (R2026a) [55]. The modelling results of Equation (9) are to be compared with that using the original van Genuchten [24] formula, which is in the form of Equation (10), and the previously proposed physical–chemical (PC) model [38,39], which was simplified in the form of Equation (11) [39]

$$S_w = \left[\frac{1}{1 + (\alpha\psi_m)^n} \right]^m \quad (10)$$

where S_w is the water saturation; ψ_m is the matric suction (Pa); and α (1/Pa), n and m are three parametric constants.

$$\psi_m = \lambda + P_0 [\exp(\alpha S_w) - \exp(\beta(1 - S_w))] \quad (11)$$

where λ , P_0 , α and β are four constants.

4. Results and Discussion

HYPROP-2 records the variation in matric suction against the water content in volume percentage of soil samples. As the water content for SWRCs takes pore water saturation degree, the recorded water volume percentage data were at first converted to the pore water saturation by normalisation using the water volume content at the point when matric suction starts at air entry moment. The water volume content values at the normalising points are listed in Table 1, which in theory should be equivalent to the porosity of the saturated soil samples, showing a positive correlation with the clay content. However, the porosity values in Table 1, which are calculated by the software of HYPROP-2, present a negative correlation with clay contents.

Although most tests were conducted by triplication, as both the sample preparation and measurements had big variation in test procedure, all final data were taken from a specific test, which is the closest to the average of triplicated tests, for the sake of data consistency. Figure 4 shows the SWRC measurements of the HYPROP-2 tests and the

modelling results using the two representative models. It can be seen that the clay amendment has significant effect on the water retention capacity enhancement compared with the control sandy soil. From the plots (a) to (d), with the clay content increase, the average matric suction value (ψ_m) increases, and the corresponding pore water content shifts to high saturation degree. For example, at $\psi_m = 100$ hPa, the pore water saturation degree (S_w) at the clay contents of 0, 15, 30 and 50% are approximately 25%, 45%, 67% and 89%, respectively. It can also be seen that the three-phase model (Equation (9)) presents a much better performance than the van Genuchten (VG) model (Equation (10)) on representing the water retention curves over the whole measurement range, particularly at low saturation or high matric suction side. Compared with the original PC model (Equation (11)), the three-phase model generally presents an improvement at the high saturation or low matric suction side. Seeing that the matric suction is plotted in log-scale, the good performance at the high suction side highlights the overall outperformance of Equation (9) covering the whole range of saturation from heavily dry to fully wet. Table 2 gives out the statistical data of the modelling results in Figure 4. The R-squared defined by Equation (12) is the proportion of the total sum of squares explained by the model; the value of unit indicates the ideal result. The root mean square error (RMSE) defined by Equation (13) is the average difference between modelling results and the experimental measurements. The static data confirm the outperformance of Equation (9) overall in general.

$$R^2 = 1 - \frac{\sum_{i=1}^n (y_i - f_i)^2}{\sum_{i=1}^n (y_i - \bar{y})^2} \quad (12)$$

$$RSME = \sqrt{\frac{\sum_{i=1}^n (y_i - f_i)^2}{n}} \quad (13)$$

where y_i stands for the experimental measurements, n is the number of experimental data, f_i is the modelling result, and $\bar{y} = \frac{1}{n} \sum_{i=1}^n y_i$ is the average of the experimental measurements.

Table 2. The statistical data of the modelling results.

Statistic Property	Model	100% Sand (Control)	85% Sand and 15% Clay	70% Sand and 30% Clay	50% Sand and 50% Clay
R-squared	Three-phase modelling	0.9899	0.9877	0.9936	0.9983
	VG modelling	0.6042	0.5865	0.8604	0.9980
	VG modelling in pF form	0.7117	0.6529	0.908	0.9979
	Original PC model	0.9936	0.9866	0.9908	0.9974
RMSE	Three-phase modelling	13.8390	20.3846	18.6415	10.2136
	VG modelling	86.6350	118.2740	86.8102	10.9459
	VG modelling in pF form	73.9451	108.3575	70.4857	11.3144
	Original PC model	10.9987	21.3141	22.3107	12.5642

Figure 5 illustrates the obtained parametric values of the three-phase model (Equation (9)). It can be noticed that the two parameters, χ and β , display a clear correlation with the clay content. In terms of the underlying physics, λ relates the initial water film state when bulk water starts to accumulate in pore volume for the wetting process or the air entry value for the drying process. It increases in absolute value with the clay content due to the increase in total pore surface area and reduction in the average pore size. On the other hand, β reflects the average total pore surface adsorption effect on the bulk vapour phase in empty pores, which decreases in absolute value when clay content increases. As clay

addition increases total pore surface area or specific surface area but reduces the average pore size, the decrease in β might indicate a decreasing effect of vapour phase on matric potential. The absolute value of the parameter α displays a decreasing trend before clay content of 30% but starts increasing thereafter. As α relates to the bulk water phase, the trend may connect to the coupling effects of soil porosity, average pore size and specific surface area. The data in Table 1 shows that the theoretical porosity (the normalising water volume content) of soil samples increases with the clay content, which lowers the average effect by the volume average of the representative volume, V_{REV} . The sharp increase after 30% clay content, however, may relate to a significant increase in the specific surface area at high clay content. The other two parameters, χ and κ , present little regular correlation with the clay content. A reasonable explanation for this could be that the two parameters relate to the states of the water film, which not only depends on the specific surface area but also the pore surface curvature. The first one enhances the adsorption force on the water film (lowering the chemical potential of water film). The second one is relevant to the particle size and shape. According to the Laplace equation, the convex shape of particles has a negative effect (activating the chemical potential) on surface water absorption as the water on a convex surface subjects a tensile stress along the surface curvature, and the negative effect is to be magnified on small particles. So, the two factors together generate a coupled offsetting influence on water film potential or pressure. For comparison, Figure 6 illustrates the variation in the parameters of the VG model (Equation (10)). All of them also show little correlative trend with the clay content. Figure 7 shows the parametric results of the original PC model (Equation (11)), where the effect of the water film is absorbed into the four parameters. At the time, only the comparison against the VG model and the previous version of the PC model was conducted because one of the advantages of the three-phase model is its easy implementation by curve fitting as a single integrated formula. It is directly comparable and aligned with the implementation of the VG model. Comparing with other recent models, although there are similar fundamental concepts, the implementation approaches have a quite big difference as stated in review before. So, no comparative study was conducted in this work.

To further investigate the advanced features of the three-phase model, it is used to estimate the pore size distribution of the soil samples based on the obtained water retention curves. According to traditional theory of capillarity, introducing in the Laplace equation, the capillary pressure P_c can be estimated in terms of the menisci at the water–vapour interfaces or the pore waterfronts (Figure 3), i.e.,

$$P_c = \frac{2\sigma}{r} \quad (14)$$

where σ is the water surface tension, which is about 0.0728 N/m under room temperature, and r is the radius of the menisci at the vapour–water interfaces. Conventionally, neglecting water film effect (P_s), the P_c in Equation (13) is simply equivalent to the matric potential, ψ_m . However, in terms of the three-phase model, P_c is evaluated by Equation (3). Using the P_c component in Equation (9) to characterise the pore size distribution, i.e., the $S_w(r)$ and $dS_w(r)/dr$, could be closer to the real value of $\frac{2\sigma}{r}$. Figure 8 compares the components P_c and P_s from the ψ_m modelling (Figure 4) but in linear scale this time. It shows that both the average capillary pressure and water film pressure over the whole range of water content increases with clay content. For P_c component, its variation range narrows and shifts from low saturation to high saturation with the increase in clay content. That aligns with the increase in the pore volume of small size and the specific surface area correspondingly. Compared with P_c , the value of P_s is much lower. So, in general, the P_c plays a dominant role in matric suction.

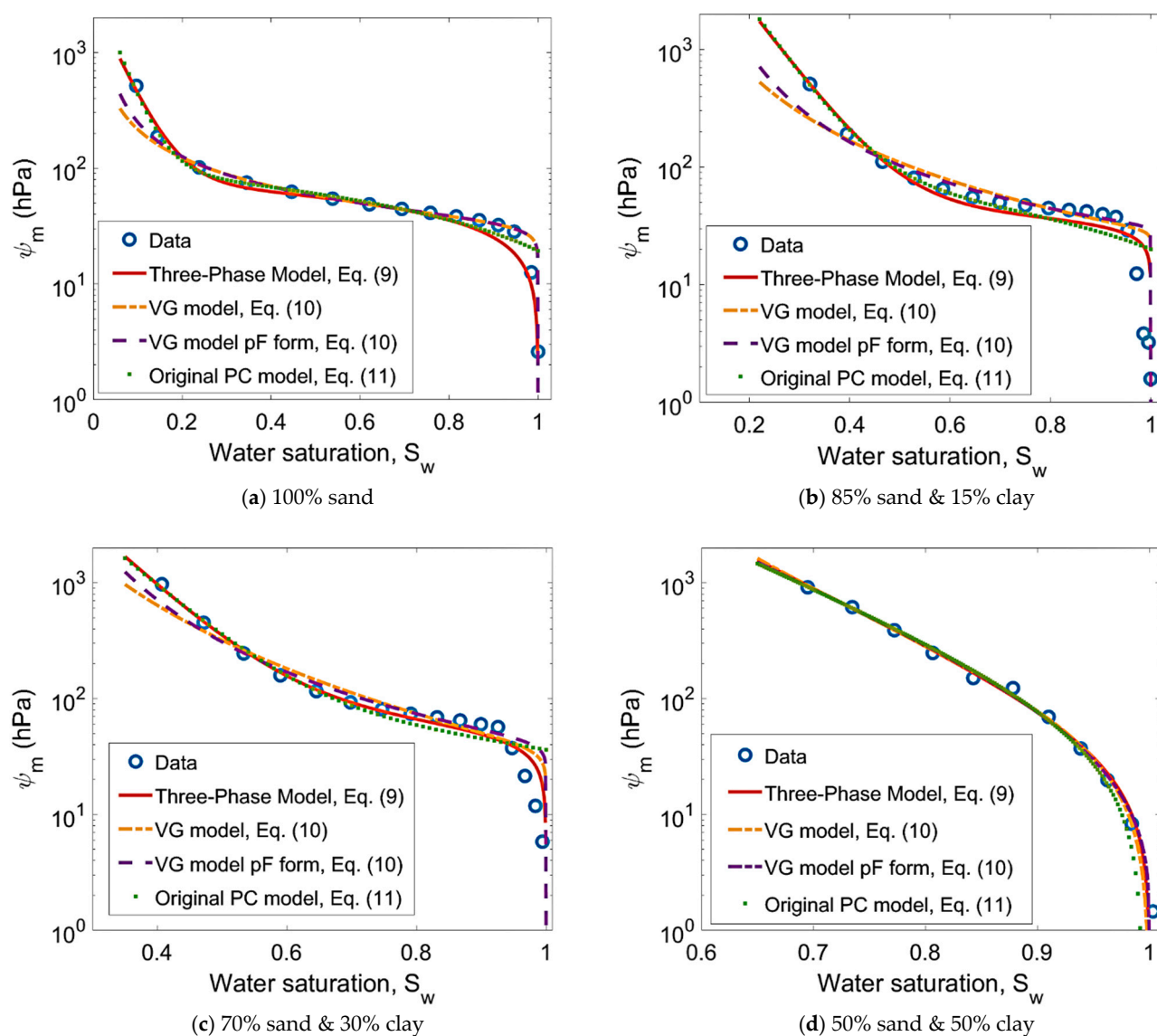


Figure 4. WRC measurements and modelling.

Figure 9 shows the calculated pore size distribution based on the P_c component in Figure 8. $S_w(r)$ curves show that the proportion of water volume in small pores increases steadily with the growth of clay content. On the other hand, the pore volume variation $\frac{dS_w(r)}{dr} = \frac{dS_w}{dP_c} \frac{dP_c}{dr}$, taking $P_c = \frac{2\sigma}{r}$, against the pore size change also increases with the clay content particularly at a small pore size range. In addition, the volume variation $dS_w(r)/dr$ presents a projective decreasing trend against the pore size for all soil samples; however, it reduces sharply at the big pore size range when clay content increases. All the results are sensibly logical.

For a comparison, Figure 10 illustrates the calculated pore size distribution, $\frac{dS_w(r)}{dr} = \frac{dS_w}{d\psi_m} \frac{d\psi_m}{dr}$ taking $\psi_m = \frac{2\sigma}{r}$, i.e., the water retention curves in Figure 4. The $S_w(r)$ curves here also demonstrate that the average pore size decreases with the increase in clay content, but the percentage of different pore sizes in total pore volume is significantly different from that in Figure 8. Except the sample of Sand 50% and Clay 50%, the $dS_w(r)/dr$ of the other three soil samples displays a spike, a major pore volume change, at the pore size range from 10 to 100 μm , but the peak value decreases with the increase in clay content. It needs to be clarified that the pore structural analysis approach and results obtained in

terms of the capillary component from the SWRC modelling using the proposed model requires further verification against soil experimental measurement.

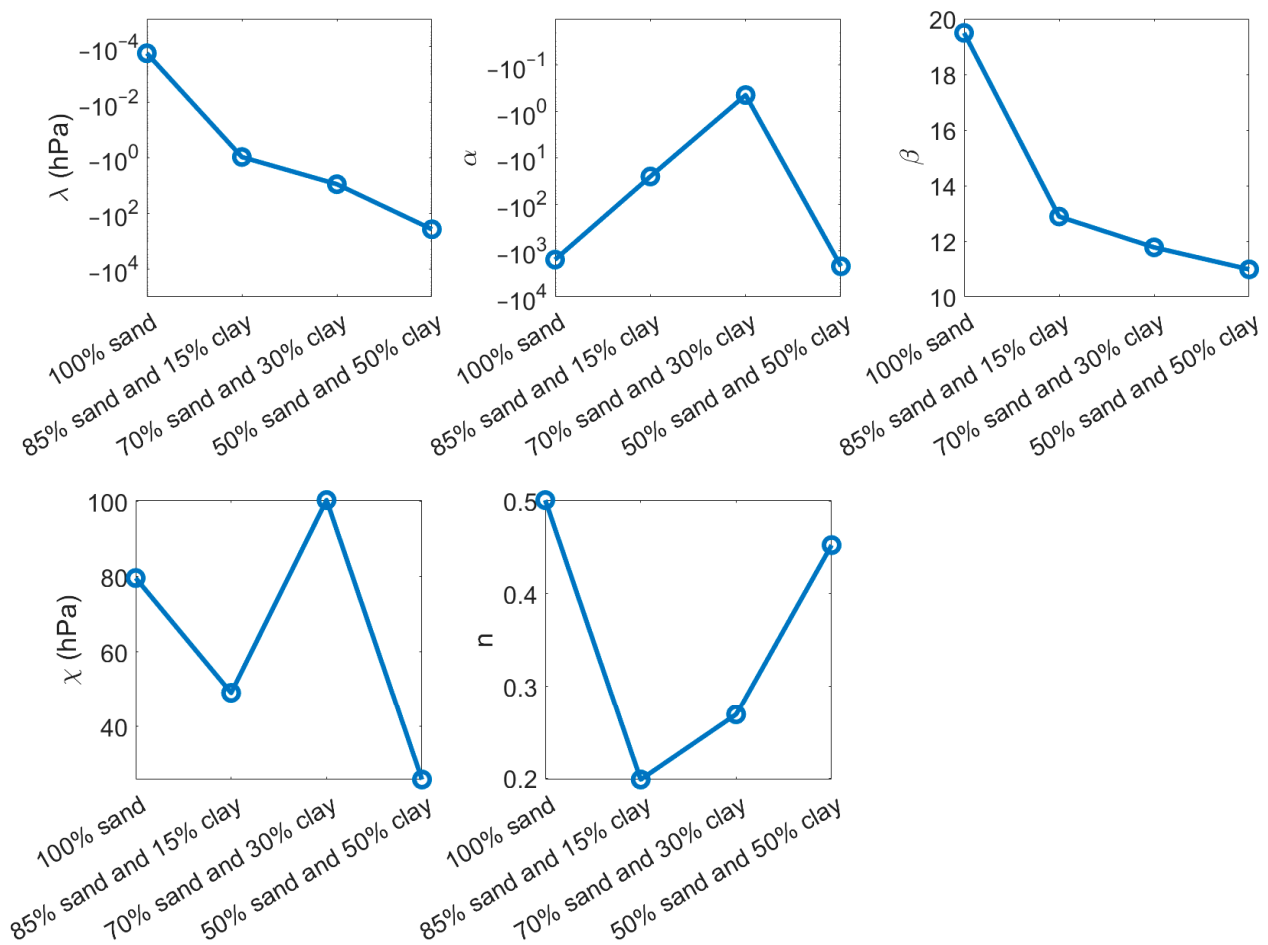


Figure 5. The results of the fitting parameters of the three-phase model (Equation (9)).

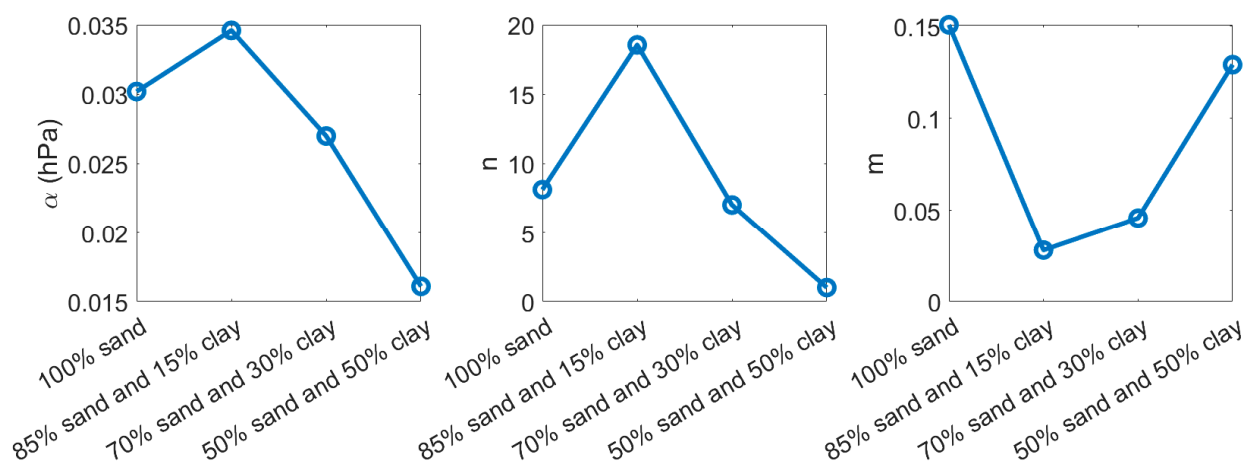


Figure 6. The results of the fitting parameters of the VG model (Equation (10)).

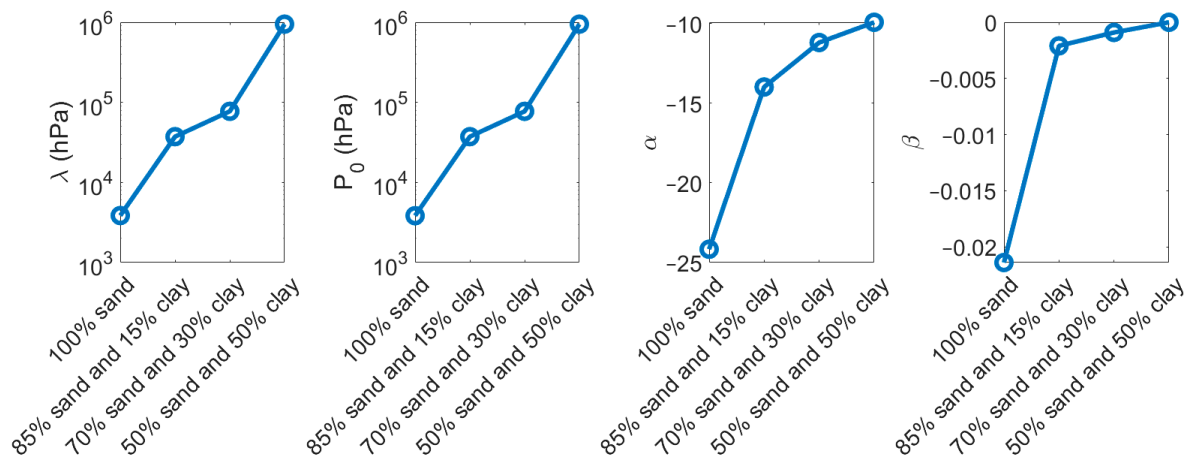


Figure 7. The results of the fitting parameters of the original PC model (Equation (11)).

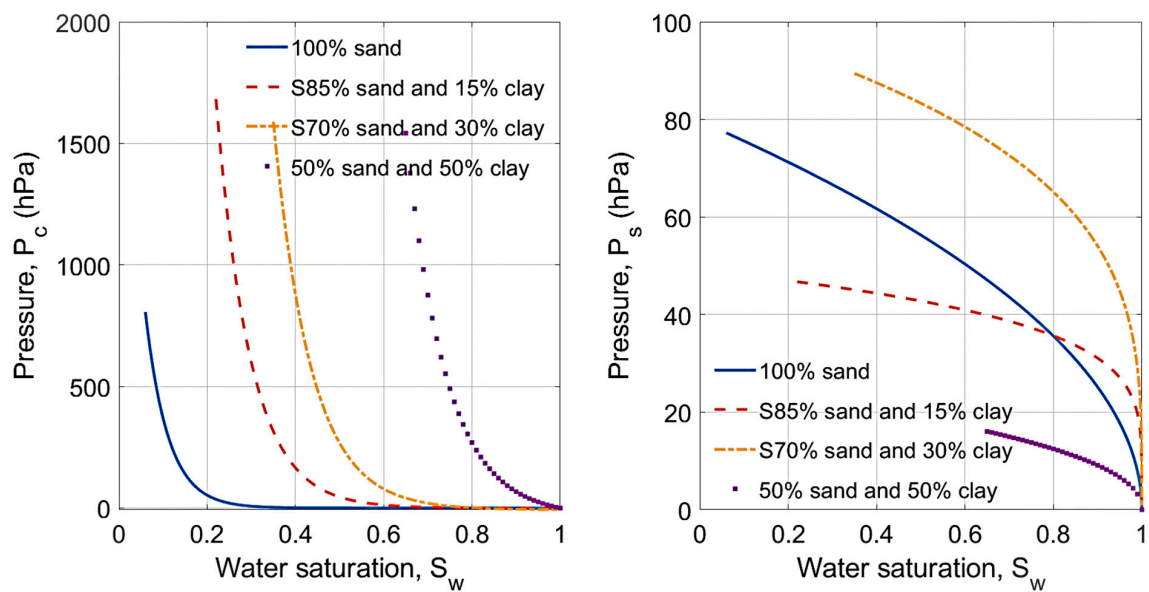


Figure 8. The pressure components P_c and P_s in the matric potential, ψ_m .

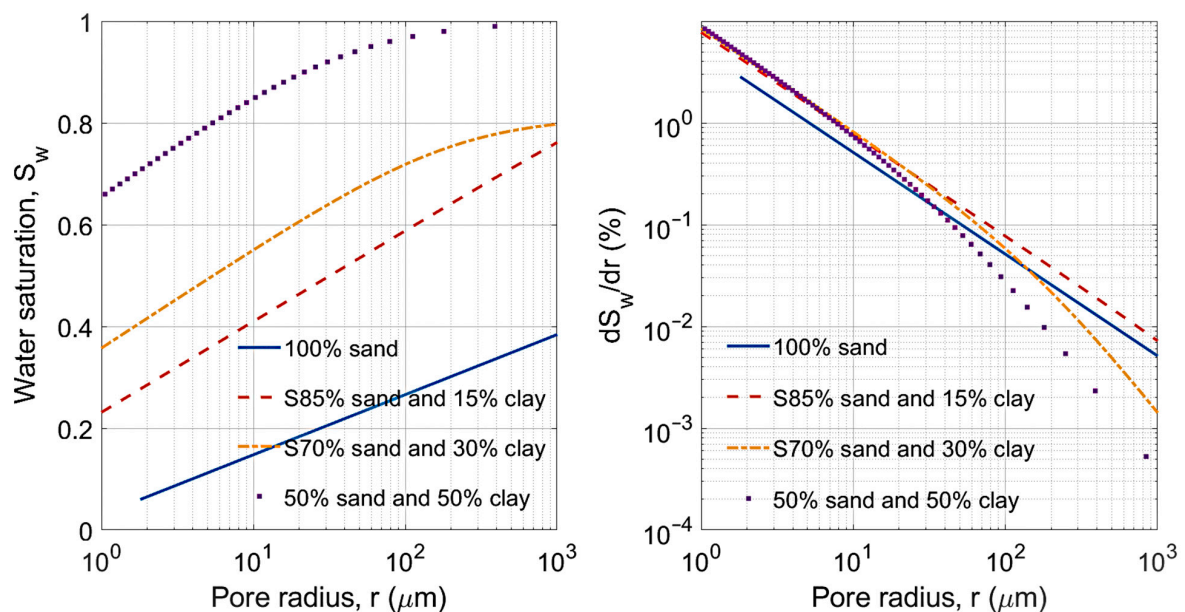


Figure 9. Pore size distribution in term of P_c component.

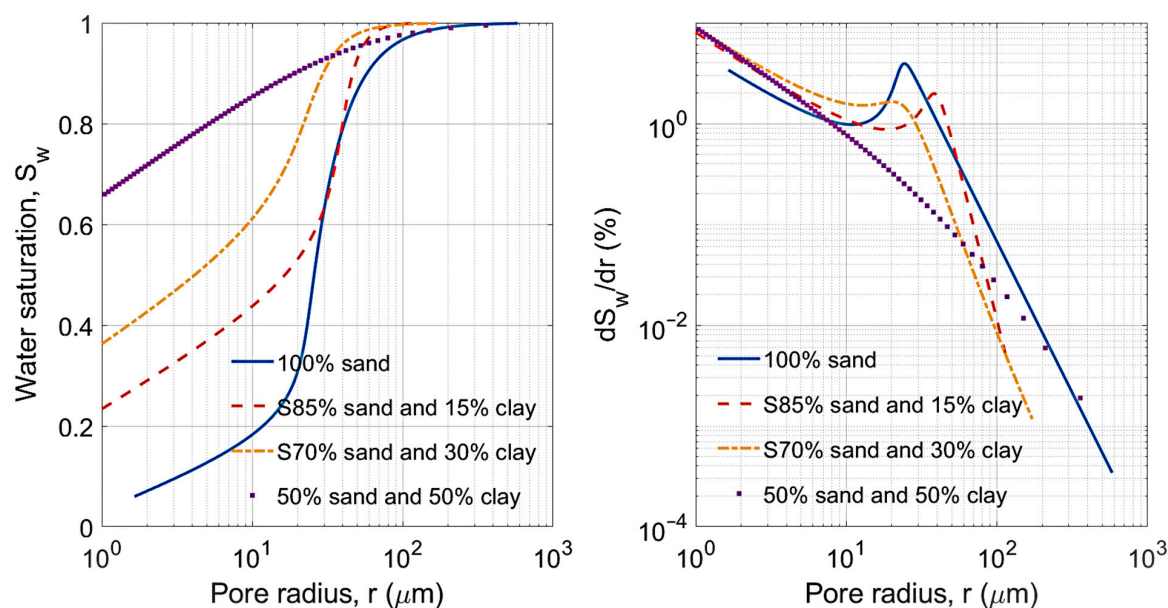


Figure 10. Estimation of pore size distribution in terms of ψ_m .

5. Conclusions

This paper reports a research work on assessment of clay effect on the water retention capacity of clayey sandy soils. It measured the water retention curves of clayey sandy soils of different clay contents. A novel analytical model was adopted for the SWRCs representative characterisation. From the study, the following conclusions can be drawn:

- The experimental tests demonstrated the effect of clay on soil water retention enhancement.
- An advanced three-phase water retention characteristic model provides a simple quick modelling tool, which has demonstrated a good performance representing the SWRCs over the entire range of soil water saturation, particularly at the low water content range, by a single curve fitting implementation.
- The advanced SWRC model provides an analytical insight into the fundamental physics underlying soil water retention mechanism. The parametric analysis and explanation in relation to the SWRCs are in good agreement with their definitions and physics functions, which highlight the influence of particle size, shape and surface curvature on the pore water retention characteristics aligned with the pore size distribution. These factors need to be considered in future research to obtain a full analytical frame for the modelling and interpretation of unsaturated water retention characteristics and its relevant applications.
- This work has also tried to interpret and estimate the pore size distribution in terms of the separated capillarity component in matric suction, an advantage of the analytical model. The results produced a big difference from that using the traditional method. However, the rigor of the new concept and approach require further experiment verification and is open to wide discussion; meanwhile, continuous research is under planning following this study.

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