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Assessment of the Effect of Soil Amendments and A Three Phase Soil Water Retention Model

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Abstract

Nowadays, using soil amendments to improve physical hydrological properties is popularly employed in agricultural engineering. This paper at first reports an experiment to compare the effect of two different soil amendments for their effect on soil water retention capacity. They two agents are the natural clay and a conditioning soil retainer. Soil water retention curve (SWRC) has been selected to quantify their effect on a benchmark pure sand soil in full range of water saturation, i.e. from fully saturated to nearly dry. Both the classic van Genuchten model and a novel three phase soil water retention model have been adopted to characterize the effect of the two soil amending agents on soil water retention capacity. The research results demonstrate that the clay has a significant enhancement on soil water retention at low content of clay and high soil water content range, however its effect reduces considerable with increasing clay content. Meanwhile the conditioning water retainer shows little effect at high soil water content range but has significant effect on soil water retention at low soil water content range. The results indicate the conditioning water retainer can help the reduction of the surface water evaporation and the water reservation underneath. The

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modelling has shown that the three-phase model is able to effectively represent the soil water retention curve in full range of soil water content, which provides a convenient tool to efficiently characterise the effect of conditioning water retainer. In addition, the three-phase model also provides the functional analysis and help understand the working mechanisms of the agents.

Keywords: soil amendment; clay; conditioning water retainer; full range soil water retention characteristic modelling.

1. Introduction

Global warming and climate change have caused unstable water supply scenarios worldwide. In Europe, freshwater shortage has been directly impacting on the agricultural industry. Both efficient management for water use and the technologies to improve the water retention capacity of soils have received high interest (Lemos et al., 2021). Nowadays, using soil amendment to improve soil physical hydrological properties is popularly employed in agricultural engineering to enhance the soil water retaining capacity and reduce nutrient loss under challenging environmental conditions (Spitalniak et al., 2019; Xerdiman et al., 2022).

There are two types of additive soil amendments in terms of their properties (Seddik et al. 2019). One type comprises natural agents sourced from clay minerals such as attapulgite, bentonite, kaolinite and zeolite (Murray, 2000). The other one is synthetics, such as biochar, superabsorbent polymer (SAP) (Huang et al., 2022), non-woven geotextiles and water absorbing geo-composites (Orzeszyna et al., 2006; Mohawesh and Durner, 2019). Both types can effectively improve soil water retention to reduce both water infiltration below the surface and evaporation at the surface (Keiblinger and Kral, 2018; Spitalniak et al., 2021).

In general, the soil water retention capacity basically depends upon the soil texture and pore structure. The underlying physical mechanisms are based on the interfacial molecular interaction forces at the soil particle surfaces and the derived condensing action due to capillarity (Dontsova et al., 2004; Zhang and Lu, 2020). The conventional assessment of the soil water retention capacity takes an approach using the soil water retention curve (SWRC), an intrinsic soil constitutive relation between the soil water content and soil matric suction. SWRC also plays a key role in the prediction for the soil hydraulic conductivity and diffusivity on the concept of their intrinsic link with soil pore size distribution and particle size. For this reason, soil water retention curve has also been widely employed to assess the influence of soil amendments on soil water retention improvement (Spitalniak et al., 2019; 2021; Wanniarachchi et al., 2019; Miller et al., 2018; Edeh & Mašek, 2022; Huang et al., 2022; Zhou et al., 2020; Wang et al., 2023).

Modelling SWRC has been a longstanding research topic (Chang and Cheng 2018; de Rooij et al 2021; de Rooij 2022). So far, numerous mathematical models have been proposed in different formulation by different approaches (Du, 2020). Among them, the mathematical formula proposed by van Genuchten (1980) is still the most popular one, which has been widely used in both hydrology and geotechnics, as it provides an effectively convenient way for the hydraulic conductivity prediction. There were many revisions ever proposed on the original van Genuchten's formula (Lima and Silva, 2022; Huang et al., 2022). In recent decades, great efforts have been made to interpret the water retention curve from both capillarity and surface adsorption to improve the modelling of soil hydrological properties, particularly from very low water content states to fully saturated state. They include the segmental modelling (Du, 2020; Wang et al., 2022), which divide the water retention curve into two different parts for the adsorption and capillarity, respectively, and a combined sorption-isotherm and capillary model (Wang et al., 2022). However, the segmental modelling may be inefficient to accurately reflect the fact that the surface adsorption and capillary condensation are coexisting at all unsaturated ranges. On the other hand, the formulas of the combined sorption-isotherm and capillary model presents a complex procedure when used for modelling characterization.

On the concept of capillarity, soil matric suction is attributed to the interfacial meniscus formed between the air and the bulk water in pore spaces, and the Laplace's equation is employed to evaluate the suction by soil pore size distribution (Dullien, 1991). On the fact that the bulk water in unsaturated soils starts to accumulate from the angular corner spaces of all pores regardless of size, Tuller et all. (1999) tried to address the water sorption and capillary contribution to metric suction within one framework. They proposed to explicitly define the soil matric suction using an augmented Young-Laplace equation consisting of two components. One is to represent the capillary pressure related to the meniscus formed at the interface of the bulk water in pores, which is evaluated by the Laplace's equation. The other one is to represent the surface adsorption force related to the water film on surfaces of empty pores. The effect of the surface adsorption force is evaluated by the water

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film thickness in terms of the concept of disjoining pressure (Iwamatsu and Horii 1996). Meanwhile a series of pore geometric model were proposed to represent the soil pore network at microscopic scale (Tuller et al. 1999). Following the work by Tuller et al. (1999), such pore-scale modelling for water retention curves (WRC) using the disjoining pressure to estimate the water film effect has also been reported by other researchers, but using different pore geometric models (Or and Tuller, 1999; Likos, 2009; Lebeau and Konrad, 2010; Tokunaga, 2011; Mohammadi and Meskini-Vishkaee, 2012; Beckett and Augarde, 2013).

Although these efforts before have demonstrated that the water film on the surface of empty pores at unsaturated states makes a significant contribution to the matric suction, there are still challenges and ineffectiveness faced by these evaluating approaches. Firstly, to rigorously calculate the adsorptive suction component requires a deterministic relationship between the water film thickness and the pore water content and vice versa. However, most of these pore-scale modelling for WRC simply used a mean-field model of the capillary condensation in a slit-type pore (Iwamatsu and Horii, 1996) to estimate the effect of the wetting film. Secondly, it is difficult to take account of the water film configuration on soil particles, because it varies with the thickness and the convex curvature of particles. The latter one theoretically consists of a negative contribution to matric suction (decrease of the matric suction). Thirdly, the pore-scale modelling generally simplifies the complexity of the realistic pore geometric shape. At last, the suction worked out at pore-scale does not equal to that at macroscopic bulk soil scale. The latter one is a volume average of all the values at individual pores. To simplify the geometric pore structure modelling, Wang et al. (2008) ever proposed a physical-chemical model for SWRC, which also starts from the concept that surface water film and condensed bulk pore water coexist in unsaturated pore network (Wang et al., 2012), but the soil matric suction is evaluated by volume average theorem.

This paper at first reports an experimental test measuring the influence of two types of soil amending agents, i.e. natural clay and a conditioning water retainer, on the SWRC. The control soil (benchmark) is pure sand, which was amended using different percentage of clay and different concentration of the conditioning water retainer. Drying soil water retention curves (SWRCs) were measured using the evaporation method starting from fully saturated up to nearly dry. The full range SWRCs were measured using two different approaches. One is using the HYPROP device to directly measure the SWRCs at low suction range or high water content range. The other one is using environmental chamber to control the relative humidity for the SWRCs at high suction range or low water content

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range. Thereafter, a new three-phase SWRC model were adopted to represent the measured SWRCs and compared with the van Genuchten modelling. Finally, the three-phase model has been employed to characterize the effect of the WR usage on SWRC.

2. Materials and Experiment

The control/benchmark soil is a pure sand with particle sizes in the range from 0.06 mm to 2 mm. One of the soil amendments is a pure clay with the maximum particle size about 500 μm. Fig. 1 shows the particle size distribution of the sand and clay. The other soil amendment is a conditioning water retainer (WR) developed by the Water & Soil® Ltd in Hungary. Unlike conventional soil amendments, such as biochar as well as mineral or polymer gel additives, which in general stand as an independent solid phase mixed into the soil particles, the WR agent here is in liquid form, which is diluted using water before applied on soils.

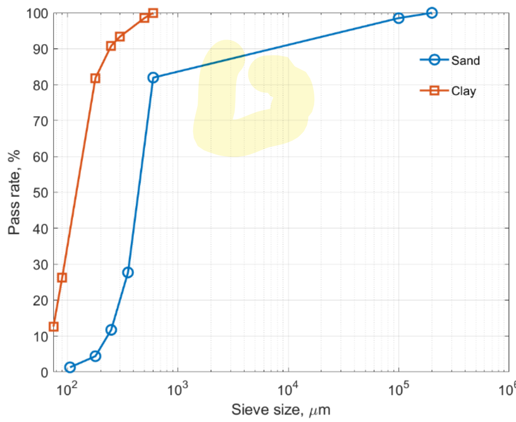

Fig. 1. Particle size distribution of the used sand and clay

The state-of-the-art equipment, HYPROP-2 (Meter Group), was used to measure the drying SWRCs curves at low suction range or high soil water content range within its measuring capacity. The corresponding part of the SWRCs in the range of high suction or low soil water content were measured indirectly by relative humidity equilibrium approach using an environmental chamber to control the relative humidity stepwise. The two measuring approaches cover a wide SWRC range

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starting from fully saturated state up to nearly dry. Table 1 lists out the prepared soil samples with and without soil amendments.

Table 1. The Soil samples for the SWRCs test

Samples	**Components**		
	Sand (% by weight)	**Clay** (% by weight)	**Water retainer** (% by volume of water)
Sand (Control)	100	0	1,2,3,5
Clayey sand A	70	30	1,2,3,5
Clayey sand B	50	50	1,2,3,5

Both sand and clay were dried separately at first in an electrical oven at 110°C for 24 hours to achieve 100% dryness before made the samples. Meanwhile, the WR was added to the distilled water to prepare the solutions of four WR concentrations by weight (1%, 2%, 3% and 5%).

2.1. Measuring SWRCs at the range of low suction or high soil water content

The tests were performed using HYPROP-2. A certain weight of the oven dried soils were taken, measured and loaded into the sample ring of HYPROP-2. The amount of the soils just reaches the full volume capacity of the rings given slightly compacting. Thereafter, the soil-loaded HYPROP-2 sample rings were put into glass containers filled with either distilled water or the WR water solution of the defined volume percentages in the Table 1. 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 unit of the HYPROP-2 were degassed and set-up following the procedure outlined in the operation menu. After 24 hours, all soil samples bathed in the containers, assumed been fully saturated, were taken out and installed on the set-up HYPROP-2 unit to start the tests. All the tests thereafter were conducted automatically until the HYPROP-2 run out of its measurement range/capacity.

2.2. Measuring SWRCs at the range of high suction and low soil water content

The tests were performed using an environmental chamber. Distilled water or the WR water solution of the volume percentages in the Table 1 was little by little added into the oven dried soils until soils became fully saturated. Thereafter, they were loaded into aluminium containers of the dimensions:

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54 mm in diameter and 30 mm in height. The saturated soil samples in the containers were further compacted using a stoper at the top to reach a height of 20 mm within the containers. Thereafter, all the prepared soil samples were weighed again and then put into the environmental chamber. The environmental chamber was set for a series of controlled relative humidity (RH) magnitudes, which were 90%, 75%, 60%, 45%, 30%, 20% and 10%, by stepwise. The soil samples were left under a certain RH magnitude for an enough long period of time. In the time, the soil water content was monitored by weighting on a scale with an accuracy of 0.01 g until the samples reached a stable state with no weight change detected for at least 1 week, when the soil pore water was assumed have reached an equilibrium state, before RH was set further down one step.

3. Results and Discussion

Fig. 2 shows the SWRC measurements of the HYPRO-2 tests. It can be seen that the clay amendment has significant effect on the water retention capacity enhancement for the control sand soil. The 30% clay content by weight has an average water saturation increase by about 3 times at a certain suction value in the range of pF = 2 ~ 3 (or suction = 100 ~ 1000hPa). However, when the clay content is over 30% the effect on soil water content increment becomes much less. The effect of the clay on water retention improvement is more pronounced at relatively low soil water content or high suction value. A logical explanation for the observation is that the clay particles increase the total pore surface area of soil samples and reduces the average pore size, which enhances the relative amount of water film absorbed on pore surfaces and the condensed bulk water in pore volume. This also explains why the effect is more pronounced at high suction end. On the other hand, the total pore surface area increase is not in a linear trend with the increase of clay content. Compared with the clay, the WR amendment has displaced little effect on water retention enhancement in the suction range, pF = 0 ~ 3, or the corresponding water saturation range, S_w = 0.2 ~ 1. Fig. 3 compares the effect on the SWRCs when WR was used for the clay amened soils. Compared with the sand soil, the WR shows increased effect helping water retention at the tested WR concentrations up to 5%, particularly for the clayey sand B.

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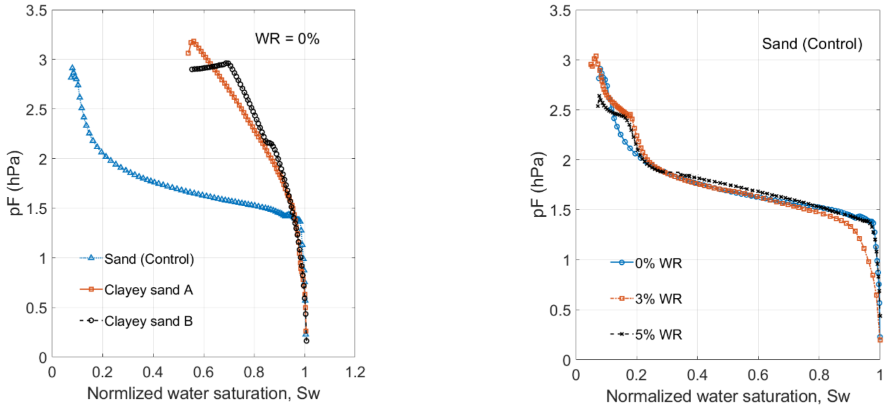
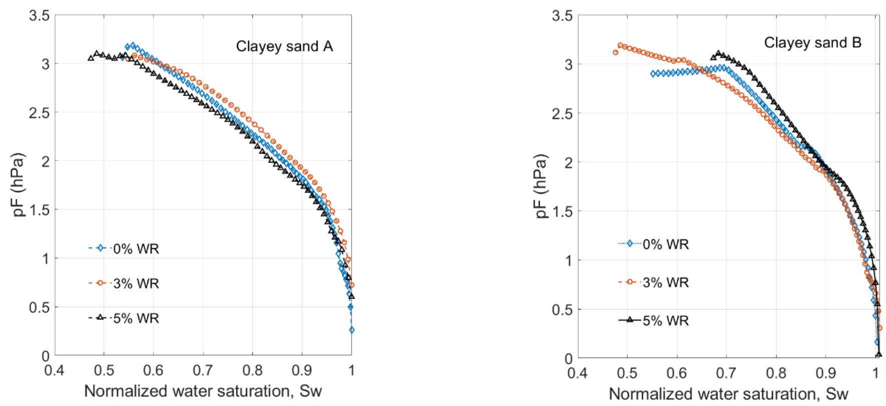


(a) The effect of clay (b) The effect of WR

Fig 2. The effect of the two amendments on SWRC at low suction range



(a) WR effect on clayey sand A (b) WR effect on clayey sand B

Fig. 3. The WR effect on SWRCs of clayey sands at low suction range

The measurements in Figs.2 and 3 show that for sand, the HYPROP-2 can only reach the maximum suction pF = 3 or the lowest water saturation S_w = 0.1. However, for the two clayey sands, the lowest water saturation can only reach at about S_w = 0.5, i.e. half saturated. For the part of the SWRCs at lower water content, the tests using the approach of relative humidity control and an environmental chamber were performed. The measurements of the environment chamber tests are given out in Figs. 4 and 5. The SWRCs are in the form of the relative humidity (RH) versus soil pore water

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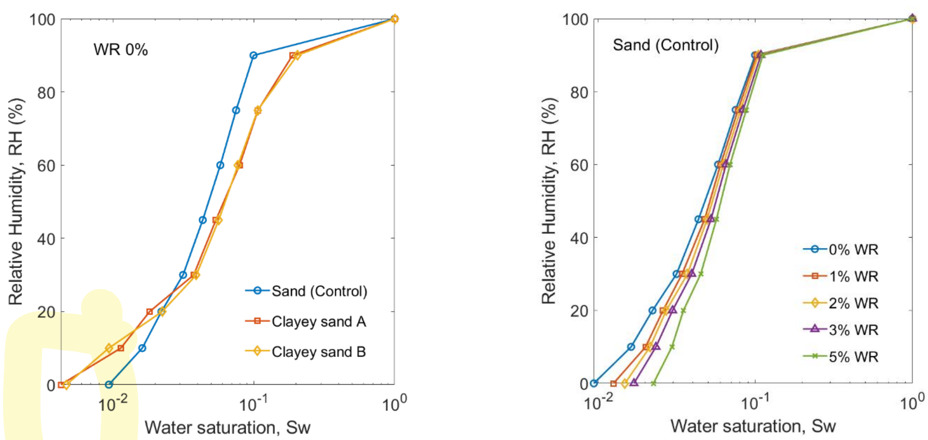
saturation. For the RH control tests, the capillary pressure or suction can be evaluated in terms of the Kelvin equation (Eq. (1)) according to Fredlund (1989).

$$\psi_m = -RTln(RH)/V_w \tag{1}$$

where ψ_m is the matric suction (Pa) with a positive value, R is the gas constant (8.314 J/mol), T is Kelvin temperature (set as room temperature at 21°C), RH is the relative humidity and V_w is the water molar volume, which is about 18.03×10^{-6} m^3/mol at room temperature.

Fig. 4(a) shows that the 30% clay amendment has the noticed effect on soil water content increase at a certain controlled RH when RH > 25%. However over 30% clay amendment, the effect almost unnoticeable. The result is in consistance with that observed in Fig. 2(a). When RH < 25%, the water retention capacity becomes worse for the clayey sands, compared to the control sand soil. This could be explained by that there is remaining pore water in clayey sands at such low water level because of the increase of inaccessible pores at that water content range.



(a) Clay effect (b) WR effect

Fig. 4. The influence of two soil amendments on the sand soil retention curves controlled by RH magnitude

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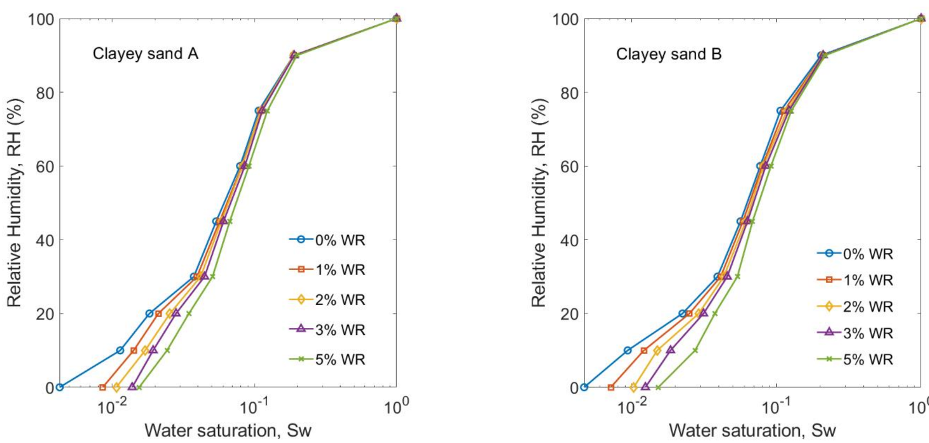
Fig. 5 compares the effect of WR amendment on the SWRCs of the clayey sand soils. Contrast to the results in Fig. 3 for the part at high water content range, it can be seen that the WR amendment displaced noticeable effect enhancing the soil water retention capacity at low water content range. The lower the soil content, the higher the enhancing effect of the WR amendment. Meanwhile, the enhancing effect increases with the WR concentration. The results indicate the WR helps enhance the amount of water in the form of the film on pore surfaces. In the other word, the WR agent particularly increases the surface force between the soil particles and the pore water film. The comparison of the Fig. 5(a) and (b) further shows that the WR effect is quite similar on both clayey sands. This reflects the previous reasoning that the total pore surface area increase is not in a linear trend with the increase of clay content.



(a) WR effect on clayey sand A (b) WR effect on clayey sand B

Fig. 5. The effect of the water retainer (WR) on the SWRCs of clayey sands at low water content

4. Soil Water Retention Characteristic Modelling

To quantify the effect of soil amendment on the SWRCs, two models were compared in this study. One model is based on the van Genuchten formula (1980) in the form of the Eq. (2).

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$$S_e = \left[\frac{1}{1+(\alpha\psi_m)^n}\right]^{\left(1-\frac{1}{n}\right)} \quad \text{(2a)},$$

$$S_w = S_r + (S_s - S_r)\left[\frac{1}{1+(\alpha\psi_m)^n}\right]^{\left(1-\frac{1}{n}\right)} \quad \text{(2b)},$$

where $S_e = \frac{S_w - S_r}{S_s - S_r}$ is the effective soil water saturation degree, S_w is the water saturation, S_r is the residual water saturation, S_s is the fully saturated water saturation; ψ_m is the matric suction (Pa); and α (1/Pa) and n are two parametric constants.

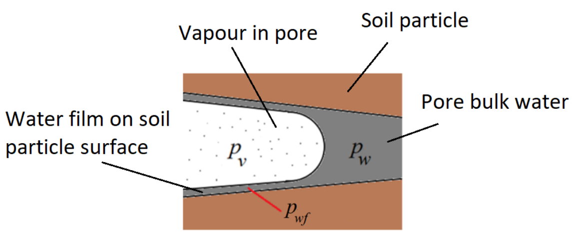

Fig. 6. The water at pore scale in unsaturated soils

p_v - pore vapour pressure; p_w - bulk pore water pressure; p_{wf} - pore water film pressure

The other one is a new three phase model, a revision on an ever-proposed physicochemical model for static water retention in unsaturated porous media (Wang el al., 2008; Wang, 2010; Wang et al., 2012). As illustrated in Fig. 6, for unsaturated soils, three water phases coexist in pore space, they are the bulk water phase in the filled pore volume; the water vapour in the empty pore volume; the water film on the empty pore surfaces. In terms of the pressure of mixtures, the pore water matric potential is determined by the state of the three phases together, which therefore can be expressed in the form of the Eq. (3) below.

$$\psi_m = P_c + P_s = (\langle p_w\rangle - \langle p_b\rangle) + \langle p_{wf}\rangle \quad (3)$$

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where, $P_c = (\langle p_w \rangle - \langle p_b \rangle)$ is the capillary pressure evaluated by the interfacial meniscus between bulk pore water and the pore vapour; $P_s = \langle p_{wf} \rangle$ is the average pressure of the entire water film on empty pore surfaces, i.e., surfaces of soil particles. The bracket, $\langle \quad \rangle = \frac{1}{V_{REV}} \int_0^{V_{pore}} dV$, is an operator for the volume average of bulk soil. The V_{REV} stands for representative elementary volume of 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, Eq. (4), below.

$$p_{fi} = p_0 \exp\left(\frac{\overline{\Delta\mu}_{fi}}{RT}\right) \tag{4}$$

where p_{fi} is the average gauge pressure of the fluid phase i on an adsorption surface (i.e. soil particle surfaces); $\overline{\Delta\mu}_{fi}$ is a local average intrinsic molar chemical potential change of the fluid phase i and it is defined as $\overline{\Delta\mu}_{fi} = \frac{1}{h}\int_0^h \Delta\mu_{fi}(z)dz$, where h 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; p_0 is a normal pressure.

According to the understanding, the volume average pressure for the bulk water phase can be worked out as: $\langle p_w \rangle = \frac{1}{V_{REV}} \int_0^{S_w V_{pore}} p_w dV$, where S_w is the pore water saturation degree. Similarly, the volume average pressure for the coexisting bulk vapour phase can worked out to be: $\langle p_v \rangle = \frac{1}{V_{REV}} \int_0^{(1-S_w)V_{pore}} p_v dV$. Substituting Eq. (4) into the integration for the volume average of pressure, the volume average of the capillary pressure can be determined as shown in Eq. (5) (Wang et al., 2012).

$$P_c = \lambda \left[\frac{1}{\alpha}(\exp(\alpha S_w) - 1) - \frac{1}{\beta}(\exp(\beta(1 - S_w)) - 1)\right] \tag{5}$$

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

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to the interfacial farce between the condensed water phase and the soil particles, while *β* is a constant relevant to the interfacial force between the vapour phase and the pore wall surfaces.

To evaluate the water film component $\langle p_{wf} \rangle$ in Eq. (3), 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. 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 (Mikhail et al., 1968; Monnier et al., 2010). De Boer et al. (1966) reviewed three empirical models which had been successfully used to represent the measurements of the nitrogen adsorption isotherms of nonporous adsorbents, which are the modified BET model (Eq. 6(a)), the Harkins-Jura model (Eq. 6(b)) and the Frenkel-Halsey-Hill model (Eq. 7(c)). The three models have become useful tools in pore structure analysis (Christos et al., 2004; Soboleva et al., 2010).

$$t = \frac{V}{V_m} = \frac{ck(p/p_0)}{(1-k(p/p_0))(1+(c-1)k(p/p_0))} \qquad (6a)$$

$$log(p/p_0) = B - \frac{A}{t^2} \qquad (6b)$$

$$p/p_0 = exp\left(\frac{-C}{t^r}\right) \qquad (6c)$$

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* and can be described using the Kelvin equation (Eq. (4)). Comparing Eq. (4) with Eq. (6c), we may obtain Eq. (7).

$$\frac{\overline{\Delta\mu}_{wf}}{RT} = \frac{-C}{t^r} \qquad (7)$$

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 this concept, a power function (Eq. (8)) is suggested here to describe the contribution of the water film to the matric suction in terms of pore water saturation.

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

where c and n are two constants; and S_w is the pore water saturation degree.

Substituting Eq. (5) and (8) into the Eq. (3), the matric potential (or suction) of unsaturated soils can be expressed in the form of the Eq. (9).

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

In the next section, Eqs. (2) and (9) are used to represent the SWRCs measured in the preceding experimental tests.

5. SWRCs Modelling

5.1. Soil water retention curves at the low suction range

Fig. 7 compares the modelling results using the van Genuchten model (Eq. (2)) and the three-phase model (Eq. (9)) to represent the SWRC measurements of the HYPROP-2 tests. The results demonstrate that both characteristic models present a good representation for the SWRC at low suction (or high-water saturation) range for all three soils at three different levels of WR application. However, when suction increases (or water saturation reduces) below a certain value, the van Genuchten (vG) model diverts away from the trend of the experimental data but the three-phase model keeps a good fit to the measurements.

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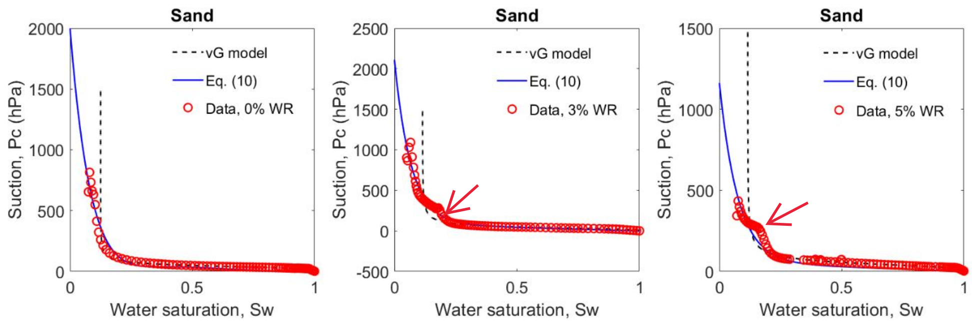
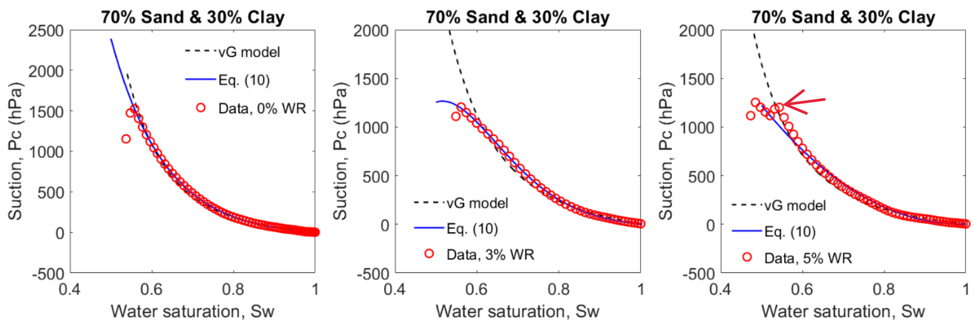
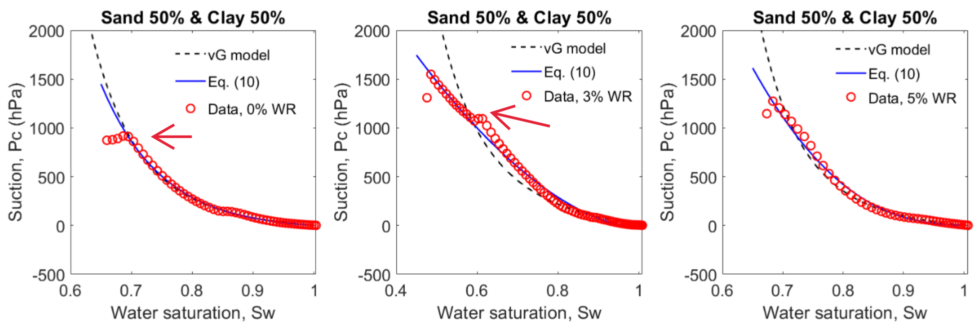


(a) Sand (Control) with three different WR applications



(b) Clayey sand A with three different WR applications



(c) Clayey sand B with three different WR applications

Fig. 7. Modelling of the SWRCs measured by HYPROP-2 tests

5.2. Soil water retention curves at the high suction range

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Figs. 8 and 9 compares the results using the Eqs. (2) and (9), respectively, to represent the SWRC measurements of the environmental chamber tests. Fig. 8 shows that the van Genuchten (vG) model is ineffectively representing both the SWRCs of all the three soils and the effect of the WR at varied application levels on the SWRC. For all measurements, Eq. (2) diverts away from the SWRC trend when the suction is higher than 124 MPa (or the controlling RH is lower than 40%). The fitting curves indicate that WR effect on water retention is particularly active at low water content and increases with the concentration.

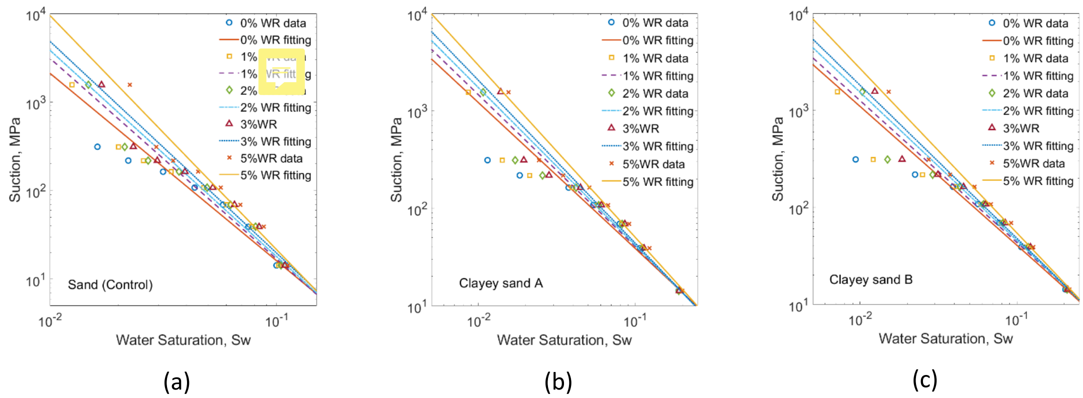

Fig. 8. The vG model modelling of the SWRCs measured by relative humidity control tests

Fig. 9 shows that the proposed three-phase model has well represented all the SWRCs measured by the relative humidity (RH) control tests. It has accurately predicted the effect of both soil amendments on soil water retention improvement in the whole tested RH range. As the soil water content in the range from fully saturated to the equilibrium state under 90% RH is that covered by the HYPROP-2 tests, and the curves in that range in the Fig.9 are almost same, so the RH control tests are consistent with the HYPROP-2 tests. The three-phase model demonstrates the ineffectiveness using the WR at relatively high soil water content range. Meanwhile it well descripts the influence of WR concentration on the SWRCs at low soil water content. A valuable notice from the modelling results is that for the 5% WR curves of the two clayey sand soils, the water retention capacity starts to decline at the high suction end (or low water content end), compared to that of the 3% WR. This can be attributed to the extremely low pore water content at the situation when the WR to water

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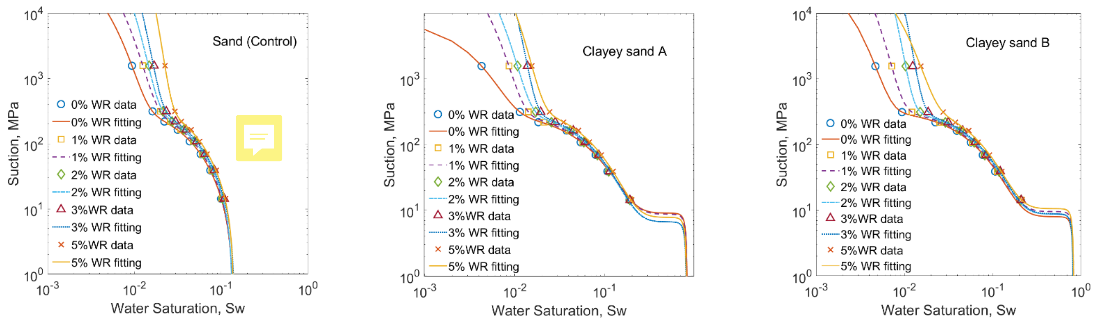
ratio is too high to work effectively. This can also explain that the decline of the 5% WR curve of clayey sand B at high suction is much faster than that of the counterpart one of the clayey sand A. As the clayey sand B has higher specific surface area, under the same water content the WR concentration in the remaining soil water, particularly for the water film on pore surface, is much higher than that of the clayey sand A.



(a) (b) (c)

Fig. 9. The three-phase model modelling of the SWRCs measured by RH control tests

The results of three-phase model can provide further understanding of WR effect on the capillary contribution (P_c) and water film contribution (P_s), respectively, in the total matric suction. Fig.10 shows the two components (Eqs. (5) and (8)) in the Eq. (9) for all the SWRCs. Align with what have been observed in Fig. 9, it can be further seen that WR helps to enhance the P_c in high suction or low soil water saturation range because WR increases the bulk water surface tension. The higher the WR concentration, the higher is the increase of surface tension. The WR also enhances the P_s, particularly at the low soil water saturation. Comparing with the P_c , P_s is deliberately presented in log-scale in Fig. 10. The comparison illustrates that WR presents much significant effect on P_s in a form of exponential trend with WR concentration. It indicates that WR is particularly active in enhancing the bonding of water film with the soil particles. It can also be clearly seen that for the clayey soil A and B samples, the P_s of the 5% WR decreases fast when the water saturations are about 1.1%. The smaller the pore size (average pore size of clayey soil B < that of clayey soil A) the flatter the curve or the less active action of the WR can be observed. Fig. 9(a), (c) and (e) show that all P_c component curves converge to zero when the pore water content reaches the state of full saturation. However,

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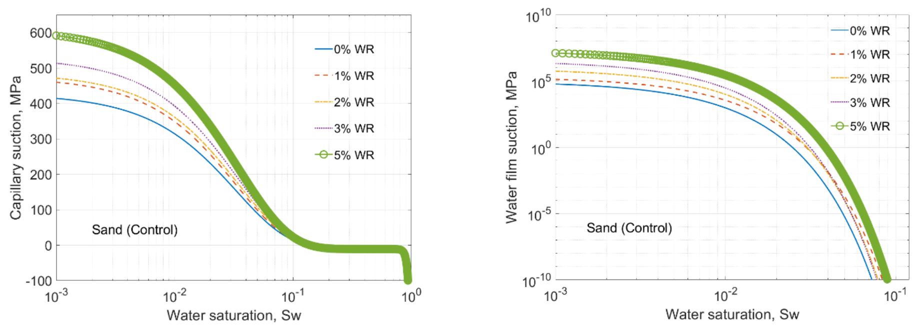
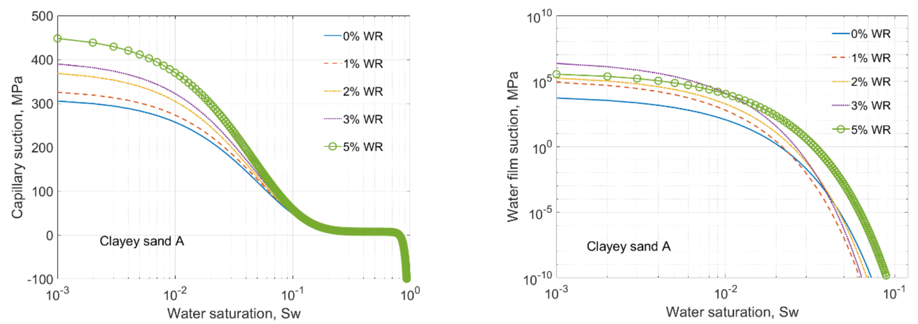
the P_s curves in (b), (d) and (f) intercept with the x-axis (suction = 10^{-4} Pa ≈ 0) at water saturation less than 1. For the clayey sand B, there is a clear trend that the higher the WR concentration the bigger the S_w of the x-axis intercept, because clayey sand B has a high specific surface area. The higher the S_w intercept on the x-axis the less the free water in fully saturated soil samples. The modelling highlights the enhancement of the WR effect with the its concentration. Overall, the three-phase model has identified all key underlying mechanisms well and is in good agreement with what has been noticed and discussed in the experiment before.



(a) Sand (Control) - P_c component (b) Sand (Control) - P_s component



(c) Clayey sand A - P_c component (d) Clayey sand A - P_s component

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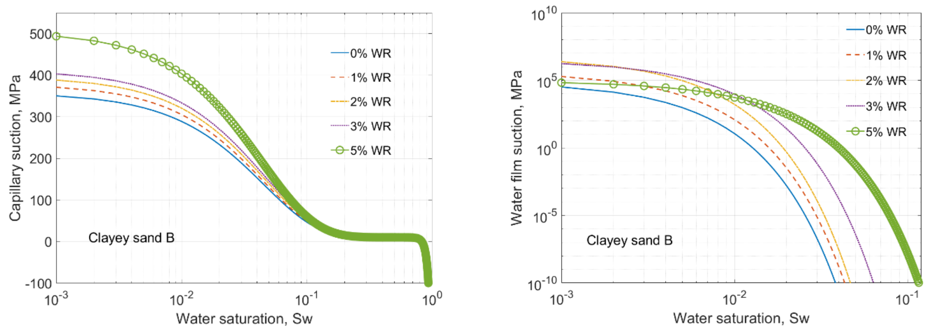

(e) Clayey sand B - P_c component (f) Clayey sand B - P_s component

Fig. 10. The capillary component P_c and the water film component P_s in the three-phase modelling

6. Characterization of the WR Concentration on the SWRCs

To provide guidance for effective use of the conditioning water retainer in soil water management practice, a characterization model for the WR concentration on the SWRCs is proposed. Unlike the clay amendment, which modifies the soil pore structure, the WR only modifies the interfacial forces between the three water phases in unsaturated soils but have no modification on the pore structure of soils. A WR effect model based on the three-phase SWRC model (Eq. (9)) is proposed in the form of the Eq. (10), as shown below. The added extra exponential term is to quantify the WR effect. The similar approach has been adopted for the characterization of other physical properties of unsaturated porous materials (Jin et al. 2017; Xiang et al. 2020)

$$\psi_m = e^{\gamma C_{WR}} \left(\lambda \left[\frac{1}{\alpha} (\exp(\alpha S_w) - 1) - \frac{1}{\beta} (\exp(\beta(1 - S_w)) - 1) \right] + \chi (1 - S_w)^n \right) \quad (10),$$

where γ is a constant, C_{WR} is the usage of the WR. For all the SWRC experimental tests, the WR was added in the water beforehand, then the prepared WR water solutions were mixed with oven dried soils up to saturated state. The SWRCs were measured by drying from a fully saturated state. In the drying process, the soil pore water evaporates, however, the WR is assumed not evaporable and remains in the soil. As the result, the WR concentration in soil pore water keeps increase with the drying process but the weight ratio of the WR to the soil samples remains a constant. Using the Eq. (10) to present all the SWRC measurements of a specific soil sample, we take the C_{WR} to be the initial WR to Soil weight ratio (WR/Soil) at the start of the saturated state. Fig. 11 displays the modelling results using the Eq. (10) to fit all the SWRC measurements in 3D space for the suction versus the

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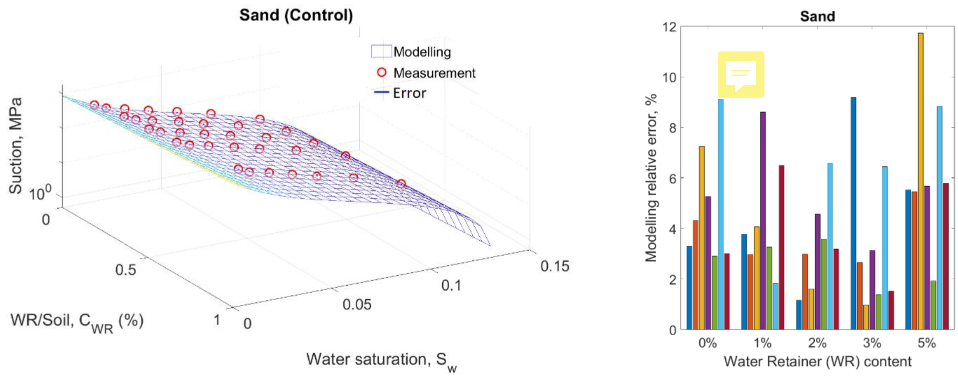
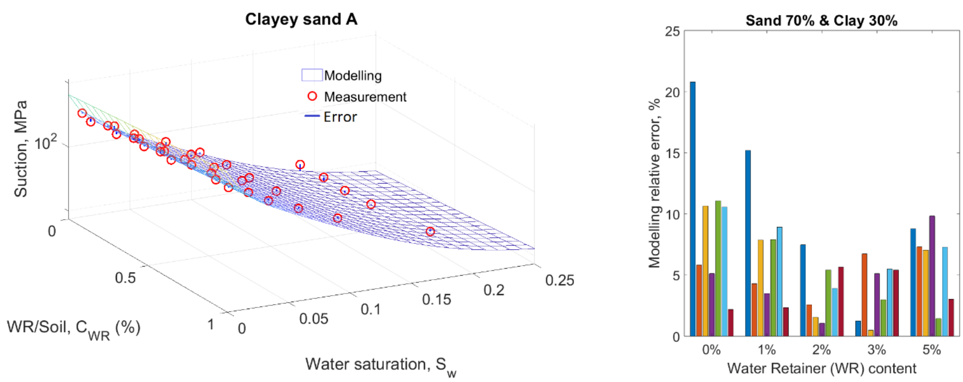
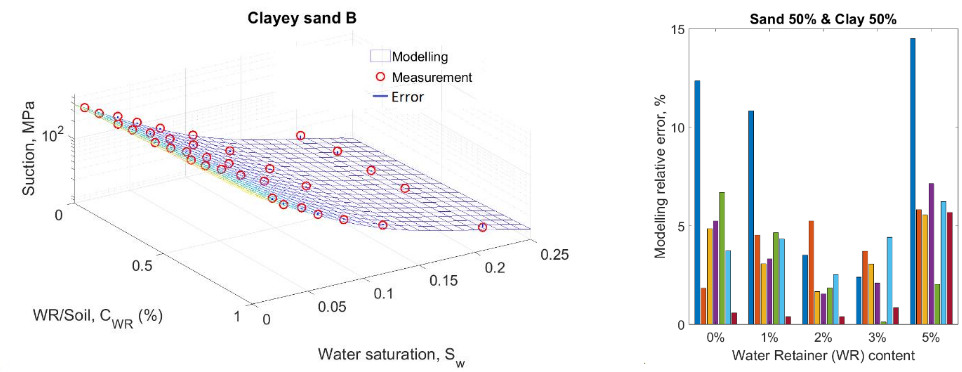
WR/Soil ratio and the soil water saturation, and the modelling relative error. It can be seen that the Eq. (10) well represents the surface of suction for all the three soils. The overall modelling average relative error is about 5%.



(a). Modelling for sand (Control)



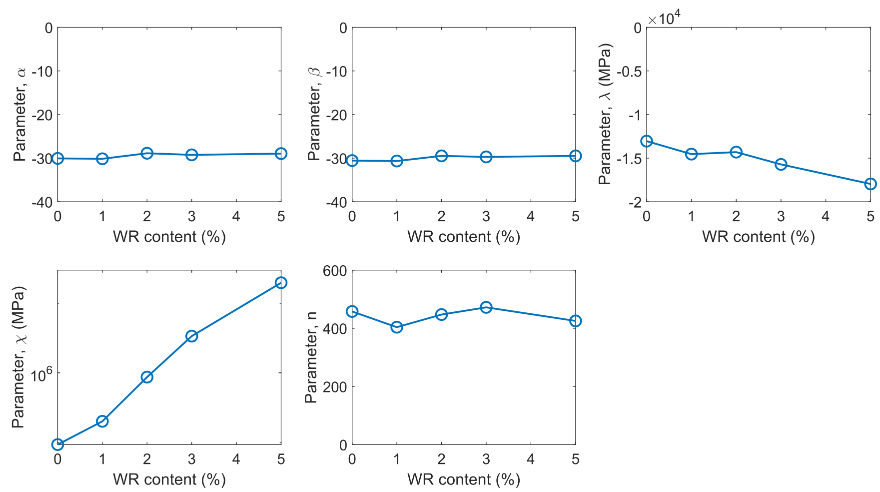
(b). Modelling for clayey sand A



(c). Modelling for clayey sand B

Fig. 11. The characterization modelling of the effect of the WR concentration on SWRCs

Fig. 12 illustrates the parametric variation of the Eq. (10) with the WR content for the three soils. It can be seen that the WR has little effect on the parameters of α and β which have a certain value for specific soils. The parameter, λ, decreases with the WR content at approximately a linear trend, while the parameter, χ, which is presented in log scale, increases exponentially until the WR at the initial saturated state reaches 3%. This is in line with previous analysis that WR particularly influences the interfacial forces between the water film and soil particles.



(a) Sand (Control)

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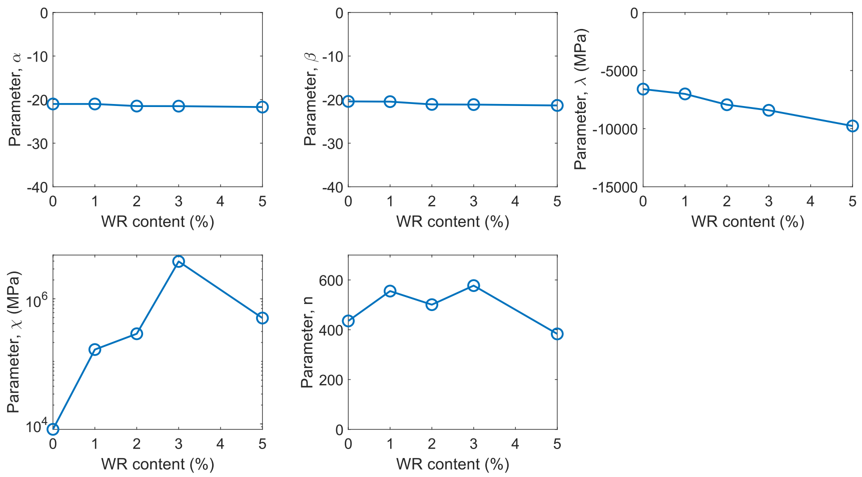
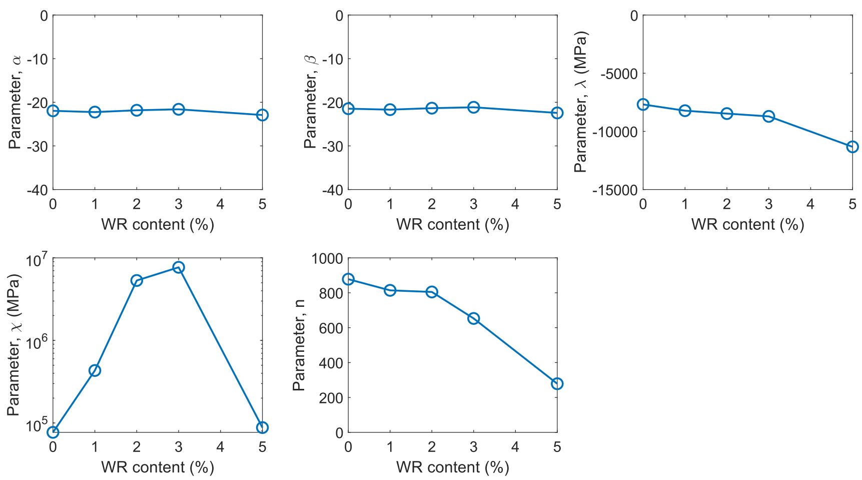


(b) Clayey sand A



(c) Clayey sand B

Fig. 12. The parametric variation of the model Eq. (10) with WC content

7. Conclusions

This paper reports research on the assessment of a natural solid and a synthesised liquid soil amendments for soil water retention improvement. The soil water retention curve has been selected to comparing their effects. Two approaches were adopted to obtain a full range of the SWRCs from fully saturated to nearly dry. A new mathematical model was proposed to represent the effect the amendments on SWRCs in full range of saturation and employed to characterize the WR concentration effect. From the results and the analysis, the following conclusions can be drawn:

- HYPROP-2 and relative humidity control approaches together have been successfully applied to assess the effect of soil amendments on soil water retention characteristic curves. The measurements are stable, and the recorded curves are smooth and complete.
- Both the tested soil amendments demonstrate the effect on soil water retention enhancement. The natural clay is more effective at high soil water content range while the conditioning water retainer primarily works at low soil water content range. The active range of 3% WR is about at the pore water saturation is less than 0.02, and 5% WR is about 0.03.
- The proposed 3-phase model demonstrates a good performance representing the SWRCs for wide range of the soil water saturation from fully saturated to nearly dry. In addition, it provides an advantage to assess the soil amendment agents effect on water film and bulk water capillarity, respectively, which helps to well understand and interpret the working mechanism of soil amendments. A derived model on it has been successfully applied to quantitatively characterize the effect of the WR usages on SWRCs. The two models can be useful tools for the WR application in water management practice.

Competing interests

The authors declare that they have no conflict of interest.

Author contribution

Yu Wang: conceived the concepts; funding application; proposed and conducted experiments and model development; experimental and modelling results analysis, discussion and presentation; write the paper.

Yirong Leng: performed experiments.

Miklas Scholz: funding application; paper editing.

Nora Hatvani: provided the conditioning water retainer; paper editing.

Vincent Uzomah: paper editing.

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Data availability statement

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The data presented are available on request from the corresponding author.

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