



Research article

Determination of the hydraulic conductivity function of grey Vertosol with soil column test

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ABSTRACT

Expansive soils exhibit swell-shrink behaviour in wet-dry periods resulting in distresses on light-weight structures founded on/in them. Therefore, it is essential to investigate the climate-ground interaction when designing structures on expansive soils. Laboratory-based models are preferred to investigate the climatic-ground interaction of expansive soils due to the uncontrollability of the boundary conditions and expenses associated with field monitoring. More flexibility in analysing the climatic-induced hydraulic responses in expansive soils can be achieved by finite element modelling of data from physical model tests. However, these laboratory-based models regularly encounter the effects of boundary flaw, preferential flow paths and entrapped air that needs to be accounted for when numerically simulated. In this study, the authors aim to numerically model the hydraulic responses in an instrumented Vertosol soil column (ISC) under controlled laboratory conditions. The effects of the preferential flow paths and boundary flaws were incorporated into a modified hydraulic conductivity as a practical approach to model the hydraulic responses in ISC. Influence of the entrapped air was rectified by a suitable correction factor. These findings present a practical method for geotechnical practitioners to accurately estimate the suction and volumetric water content profiles in laboratory-based expansive soil model tests.

1. Introduction

The ground response of unsaturated expansive soils due to the climatic changes pose difficulties for the construction industry. Swell-shrink behaviour of these soils during wet and dry seasons imposes stresses on light weight structures. This has been comprehensively reviewed in the literature (Aitchison and Peter, 1973; Day, 1994; Al-Shamrani and Abdullah, 1999; Briaud et al., 2003; Fityus et al., 2005; Ito and Azam, 2010; Nelson, 2015; Rao et al., 2004; Cheng et al., 2017; Gao et al., 2017; Khan et al., 2017; Udukumburage et al., 2019a,b). However, this shrink-swell phenomenon only affects a certain depth; known as 'active zone depth'. According to Australian Standard on residential slabs and footing design (AS 2870, 2011), active zone depth of Brisbane soils can be considered within the range of 1.5–2.3 m and is highly dependent on regional climatic conditions. The studies conducted by Masia et al. (2004) and Costa et al. (2014) identified the active zone depth of Australian soil varied from 1.0 - 4.5 m and 0.6–3.0 m, respectively depending on soil type and location. Their research demonstrates a considerable variation of the active zone depth for Australian soils; which

need to be verified. Limited research has been conducted to investigate the actual active zone depth in the Brisbane region and little to no site monitoring has been carried out.

Expansive soil behaviour in response to climatic variations is a critical phenomenon needing further investigation for structural and geotechnical design purposes. Field investigations in expansive soils conducted by many researchers (Fityus et al., 2004; Ng and Zhan, 2007; Hu and Azam, 2008; Gallage et al., 2009; Karunarathne et al., 2014; Chan et al., 2015) found that expansive soil monitoring is extremely time-consuming, costly and laborious. To avoid the complexities involved in field monitoring expansive soil laboratory model studies have been conducted under controlled laboratory conditions to investigate the climate-ground interaction (Cui et al., 2008, 2013; Tang et al., 2009; Schanz et al., 2013; Ng et al., 2016; Gallage et al., 2017). These laboratory model tests present a convenient and controlled alternative for field monitoring of expansive soils; however, the degree of freedom for a parametric study is limited due to time, cost and labour constraints.

Numerical modelling of expansive soils has been considered a viable option to simulate the ground conditions in terms of hydraulic and

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mechanical behaviour and investigate the soil response to different climatic conditions (Masia et al., 2004; Gitirana et al., 2005, 2006; Benson, 2007; Ito and Hu, 2011; Rajeev et al., 2012; Adem and Vanapalli, 2013; Costa et al., 2014; Ito et al., 2014; Li et al., 2016; Karunarathne et al., 2018).

Climate-ground response in terms of hydraulic behaviour has been broadly discussed in studies conducted by Gitirana et al. (2005), Gitirana et al. (2006), Benson (2007), Rajeev et al. (2012), Costa et al. (2014) and Li et al. (2016). In these studies, modelling of hydraulic responses in soils were conducted by finite element software: VADOSE/w. Alternatively, software like SVFlux (Gitirana et al., 2005, 2006; Benson, 2007; Ito and Hu, 2011; Ito et al., 2014), Hydrus (Benson, 2007) and UNSAT-H (Benson, 2007) are also used for finite element modelling on different types of soils. The finite element model studies described below provide information regarding different aspects of FE modelling.

The effect of the infiltration boundary condition on the variation in soil volumetric water content and suction profiles were investigated by Gitirana et al. (2005). Different precipitation rates were numerically modelled using SVFlux and VADOSE/w software and good agreement was found between them. Gitirana et al. (2006) modelled soil atmosphere interaction (evaporation) for sand material using SVFlux and VADOSE/w. Both model predictions were in good agreement with the laboratory experiment conducted on sand material by Wilson (1990).

Masia et al. (2004) discussed the importance of the initial soil suction profile, hydraulic conductivity parameters and the top surface suction change in the soil for accurate hydraulic modelling. In the absence of actual initial suction profile, the hydraulic model requires 3–5 years of climatic data to determine a representative initial suction profile (Masia et al., 2004). Masia et al. (2004) also identified that the suction change at the ‘true soil surface’ is not representative of the state of the soil; hence, surface suction change of soil should be deemed slightly below the ‘true surface’.

Li et al. (2016) numerically simulated the climatic effect on the wetting front depth of loess soil in China. A FE model was developed and validated using the volumetric water content responses obtained from the field investigations. Based on the findings of Li et al. (2016), the changes in volumetric water content in response to environmental changes become less pronounced with depth. Li et al. (2016) also found that volumetric water content (VWC) at some depths remained almost constant compared to above and below levels due to dynamic stabilization state at that depth.

Recently, Karunarathne et al. (2018) developed a coupled model using VADOSE/w to predict the ground moisture and suction response profiles due to climatic changes in Melbourne, Australia. The initial soil suction profile was determined based on the field observed volumetric water content profile and laboratory determined soil-water characteristic curve (SWCC). The model was validated by comparing the field measured (Melbourne, Australia) and model-predicted volumetric water content values. A major finding of Karunarathne et al. (2018) was that the thermal properties of expansive clays have extremely low sensitivity for variation in volumetric water content.

From the limited numerical simulations conducted on expansive soils, the effect of the prolonged rainfall/flood conditions on the hydraulic responses (change in water content and suction profiles) have not been comprehensively investigated; especially for grey Vertosol. The flood conditions cause severe changes in soil moisture and suction which results in ground heave in expansive soils whereas collapsible soils and granular materials display shrinkage characteristics and insignificant volume changes, respectively. To investigate the climate-ground interaction of grey Vertosol in terms of soil suction and volumetric water content, the authors constructed a large instrumented soil column. One-dimensional preliminary finite element model (FEM) was developed using SEEP/w (2018 version: the improved version of VADOSE/w) based on the known material properties, initial conditions and boundary conditions. The developed FEM was further calibrated

for preferential flow paths and validated using the experimental volumetric water content responses during the wetting process. This paper proposes a practical approach to investigate the climatic induced hydraulic response in expansive soils and associated correction factors (i.e. preferential flow paths and entrapped air) for laboratory-based expansive soil model tests.

2. Test material, apparatus and numerical tools

2.1. Test materials

Natural expansive clay collected from Sherwood, Queensland in Australia was used in this study. Soil classification tests were conducted according to Australian Standards as per Table 1 and classified as CH (Clay of High Plasticity) according to the Unified Soil Classification System (USCS). The results from the X-ray diffraction (XRD) analysis were used to verify the composition of montmorillonite (22%) and kaolinite (73%) clay minerals which contribute to the expansive nature of the soil.

Figure 1 depicts the Soil-Water characteristic curve (SWCC) of the soil obtained from different suction measuring methods: tensiometer (0–90 kPa), water potential sensors – MPS6 (100 kPa–4000 kPa) and WP4C Dewpoint Potentiometer – Psychrometer (4 MPa–30 MPa) (Gallage et al., 2017). The measured data points in Figure 1 are fitted using Fredlund-Xing (F-X) equation (Fredlund and Xing, 1994). The F-X fitted SWCC provided the curve fitting parameters: residual soil suction (Ψ_r), saturated volumetric water content (θ_s), fitting coefficients (a, n, m) as shown in Figure 1. These fitting parameters define the inflection point and the slope of the SWCC.

2.2. Test apparatus

The climatic-ground interaction of grey Vertosol soil can be investigated using an instrumented soil column Udokumburage et al., 2020. The testing apparatus used in this study is comprehensively discussed in expansive model studies conducted by Udokumburage et al. (2018). Figure 2 demonstrates the schematic diagram (Figure 2a) and physical model (Figure 2b) of the testing setup that was used during the experiment. The basic soil properties and the sensor arrangement are presented in Table 2. The homogeneity of the soil column was maintained when preparing the soil material and compacting into small lifts (50 mm). Initially, expansive grey Vertosol soil was oven-dried, ground and mixed with water to reach 15% gravimetric water content, and then stored in air-tight containers for 7 days to moisture homogenise the samples. To maintain the homogeneity of the soil column, soil layers were evenly compacted in 50 mm soil lifts as in Tang et al. (2009) and Gallage et al. (2017). A Mariotte's bottle is attached to the soil column to apply constant head wetting front (Ng et al., 2016). The testing apparatus is capable of measuring the soil suction at 50 mm, 150 mm, 300 mm and 500 mm levels (Figure 2a). Volumetric water contents at 50mm, 150 mm, 300 mm and 800 mm subsoil depths can be monitored using this instrumented soil column (Figure 2a).

2.3. Numerical modelling tools

Finite element modelling of a soil column can be conducted based on the knowledge of ‘Representative Elemental Volume’ (REV) and, governing partial differential equations for mass transfer and mass conservation. This study is based on the water infiltration in unsaturated soil and hence the water storage condition of REV changes with time (transient condition). Partial differential equation of mass conservation for two-dimensional water flow (without any sink or source) is as follows.

Table 1. Soil classification tests results.

Classification Test	Results	Standard
Grain size distribution	% finer than 75Mm > 77%	AS 1289.3. 6.3 (2003)
	Fraction of clay = 50.1 %	AS 1289.3.5.1 (2006)
Atterberg Limits	LL = 67.0 %	AS 1289.3.4.1 (2008)
	PI = 37.2 %	AS 1289.3.1.1 (2009)
Linear Shrinkage	LS = 13.39 %	AS 1289.3.2.1 (2009)
X-ray diffraction (XRD)	Presence of Smectite minerals	
Specific Gravity	G _s = 2.67	AS 1289.3. 6.1 (2009)

Note: LL = Liquid limit; PI = Plastic index; LS = Linear shrinkage.

$$\frac{\partial \left(k_x \frac{\partial h}{\partial x} \right)}{\partial x} + \frac{\partial \left(k_y \frac{\partial h}{\partial y} \right)}{\partial y} = \frac{\partial \theta}{\partial t} \tag{1}$$

where;

- $\frac{\partial h}{\partial x}, \frac{\partial h}{\partial y}$ = Hydraulic gradients in x and y directions
- k_x, k_y = Hydraulic conductivity in x and y directions
- $\frac{\partial \theta}{\partial t}$ = Rate of change in volumetric water content in soil (storage)

Investigation of pore water pressure variations with time can be conducted after rearranging Eq. (1) as Eq. (2). The change in volumetric water content per unit time can be re-written using the pore water pressure, unit weight of water and the slope of SWCC.

$$\frac{\partial \left(k_x \frac{\partial h}{\partial x} \right)}{\partial x} + \frac{\partial \left(k_y \frac{\partial h}{\partial y} \right)}{\partial y} = m_w \gamma_w \frac{\partial H}{\partial t} \tag{2}$$

where;

- m_w = Slope of the volumetric water content function
- γ_w = Unit weight of water
- $\frac{\partial H}{\partial t}$ = Rate of change in total head

Isotropic and homogeneous conditions are assumed for the expansive soil material. In order to simplify the numerical analysis, one-dimensional flow can be assumed and hence Eq. (3) can be derived from Eq. (2). In this equation, the right side represents the storage of water in a representative soil volume with change in delta time. Assuming the slope of the SWCC function (m_w) and unit weight of water (γ_w) are constant, these can be taken out from the derivative function.

$$\frac{\partial \left(k_y \frac{\partial h}{\partial y} \right)}{\partial y} = m_w \gamma_w \frac{\partial H}{\partial t} \tag{3}$$

Total head value ascertained for a REV can be used to continue the calculation for the entire domain using transient finite element equation (Eq. 4). If initial total head is known, this equation ascertains the final total head after given time step. As this is an iterative process, every time step re-iterates the value for final total head based on the initial total head for the given time step. For the next time step, the initial total head would be the final total head from the last time step. The mass matrix consists of the volume (or area) and the rate of change in volumetric function; and finally, accounts for the storage of water.

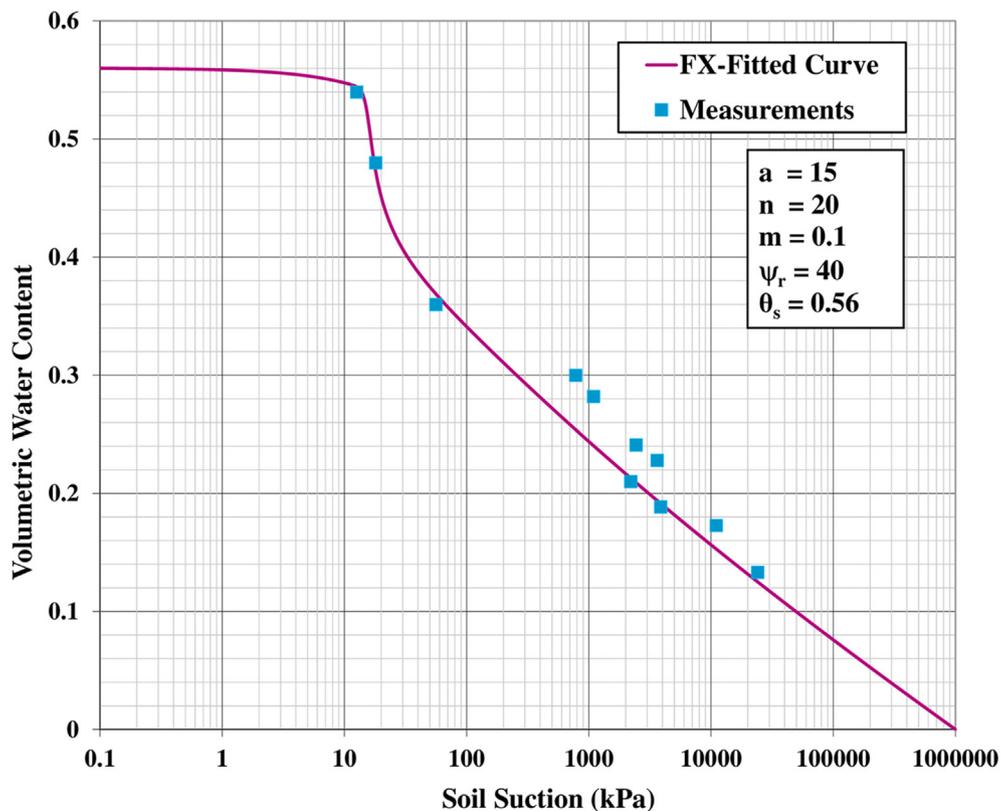


Figure 1. Soil water characteristic curve of grey Vertosol.

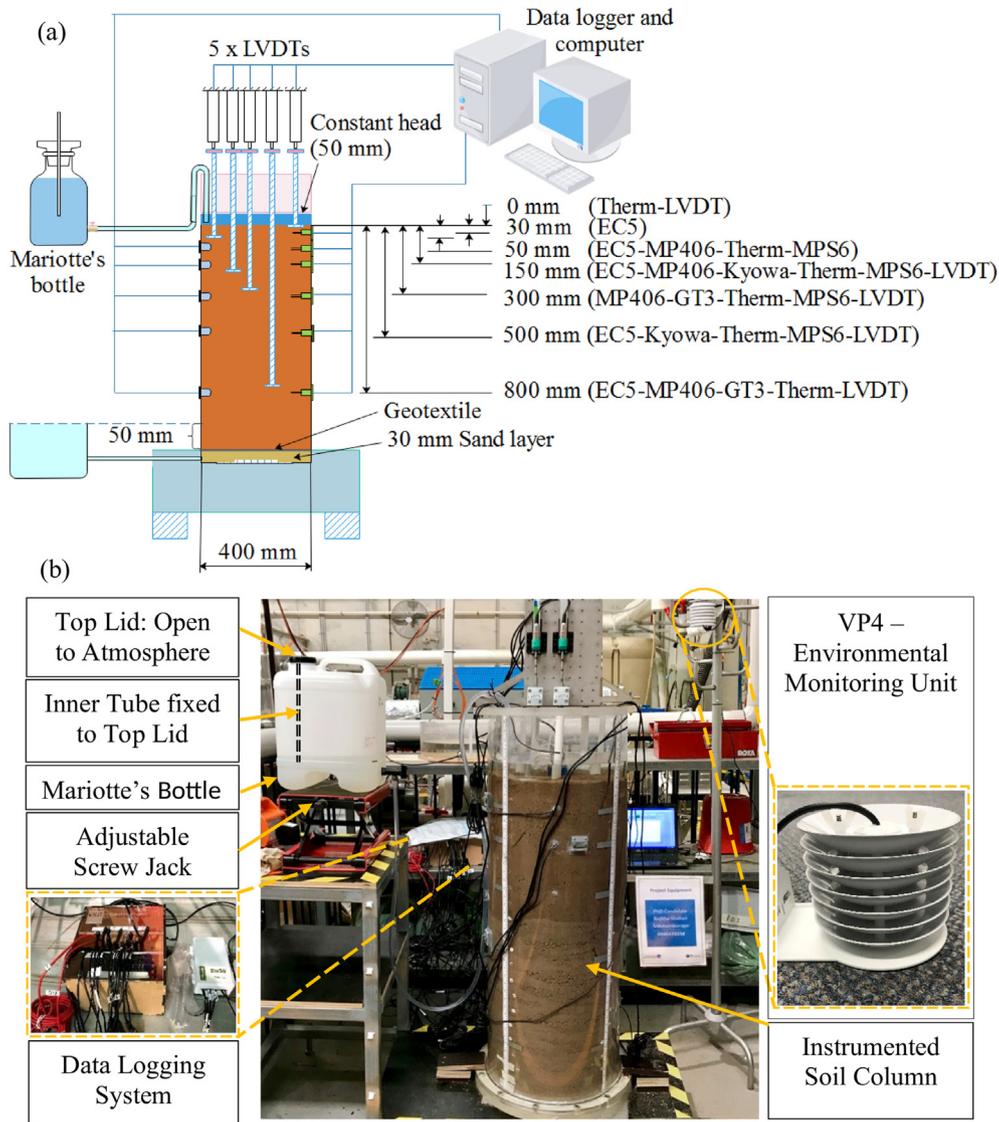


Figure 2. Instrumented soil column: (a) schematic diagram (b) physical model.

$$\Delta t[K] + [M]\{H_1\} = \Delta t\{Q_1\} + [M]\{H_0\} \tag{4}$$

where;

- H_0 = Initial total head of REV (Initial condition) for a given time step
- H_1 = Final total head after Δt time step (Final condition) for a given time step
- Δt = Time step
- $\{Q_1\}$ = Boundary condition for the time step or Nodal flow (flow vector)
- $[M] = f(\text{area}, m_w)$ = Mass matrix; which accounts for storage
- $[K]$ = Hydraulic conductivity function
- $\{H_0\}, \{H_1\}$ = Vectors of initial and final total heads

Soil water characteristic curve (Figure 1) and hydraulic conductivity curve have been utilized as material model input functions to determine the unsaturated soil characteristics of expansive soil.

3. Methods

The operation of the physical soil model, development and validation of the one-dimensional finite element model to investigate the climate-ground interaction are comprehensively discussed in this section.

Section 3.1 presents the experimental study conducted based on the soil column test (physical model) and, Section 3.2 describes the numerical modelling and validation procedure.

3.1. Soil column test and data collection

The instrumented soil column was subjected to 0.05 m constant pressure head throughout the wetting period of 160 days. This replicates

Table 2. Parameters used for Instrumented Soil Column (ISC) setup.

Parameter	Value	Remarks
Initial water content (VWC)	18 %	Observed field moisture
Initial dry density of soil	1.2 g/cm ³	Observed field density
Constant pressure head at top	50 mm	Controlled top wetting
Number of moisture sensors	4	MP406 sensors were used
Number of LVDT sensors	5	LVDT-settlement attachments
Number of Suction sensors	4	MPS6 sensors were used
Number of days in wetting process	160 days	Induced rainfall for 160 days

VWC - Volumetric water content LVDT - Linear Voltage Displacement Transducers.

the climate-ground interaction of uncracked expansive soil under prolonged rainfall conditions. Ground responses were monitored by the variations of the volumetric water content and suction sensors embedded at known levels. Refer Figure 2 for more information. The sensor responses were captured using a dedicated data logging system designed at the Queensland University of Technology (QUT). LabVIEW programme was used as the software platform/interface and the data were acquired for every 1-minute interval. The calibrated data collected for 160 days period were used to determine the temporal variations of volumetric water content and suction profiles. These experimentally determined profiles imply the climatic-induced ground responses of uncracked expansive soil (grey Vertosol) under wetting condition.

3.2. Numerical model development

In this study, authors are more focused on hydraulic response modelling in expansive soils. Numerical modelling of climate-ground interaction was conducted for 160 days using SEEP/w software (2018-R1 version). Figure 3 shows the finite element model formulation procedure.

Initially, 1-dimensional seepage model was developed using the known hydraulic material properties (Section 3.2.1), hydraulic boundary conditions (Section 3.2.2) and initial model conditions (Section 3.2.3). The developed FE model was run for a predefined time-step condition to predict the moisture and suction responses of the physical model (soil column). The developed preliminary FE model was calibrated using the actual experimental suction profile responses. The model calibration is

elaborated in Section 3.2.1 as it involves adjustments to hydraulic conductivity function. Finally, the FE model was calibrated using experimental (actual) moisture profile observed from the physical model.

3.2.1. Material properties

Finite element modelling of the hydraulic behaviour of expansive soils require soil-water characteristic curve (SWCC) and unsaturated hydraulic conductivity function (Ito et al., 2014). Soil water characteristic curve presents the fundamental relationship between the volumetric water content (θ) and the soil suction (ψ) (Fredlund, 2002; Gallage et al., 2009; Abeykoon et al., 2017). The experimental volumetric water contents and corresponding suction values can be fitted using several methods; however, Fredlund and Xing (1994) is more preferred for expansive soils as it represented the field results better than other established methods (Karunaratne et al., 2018).

The hydraulic conductivity function of expansive soils is important to simulate the unsaturated hydraulic behaviour of reactive soils. Determination of unsaturated hydraulic conductivity function under laboratory condition is extremely challenging and time-consuming (Fredlund et al., 1994; Barbour, 1998). Therefore, most numerical studies employ an estimated function (Fredlund et al., 1994) from saturated hydraulic conductivity and SWCC (Karunaratne et al., 2018). In this study, the unsaturated hydraulic conductivity function was derived from the known saturated hydraulic conductivity (K_s) and SWCC (Figure 1) according to Fredlund-Xing method (Fredlund et al., 1994).

Due to the clear mismatch between the experimental and FE model predicted soil suctions, the reason behind the disparity was investigated.

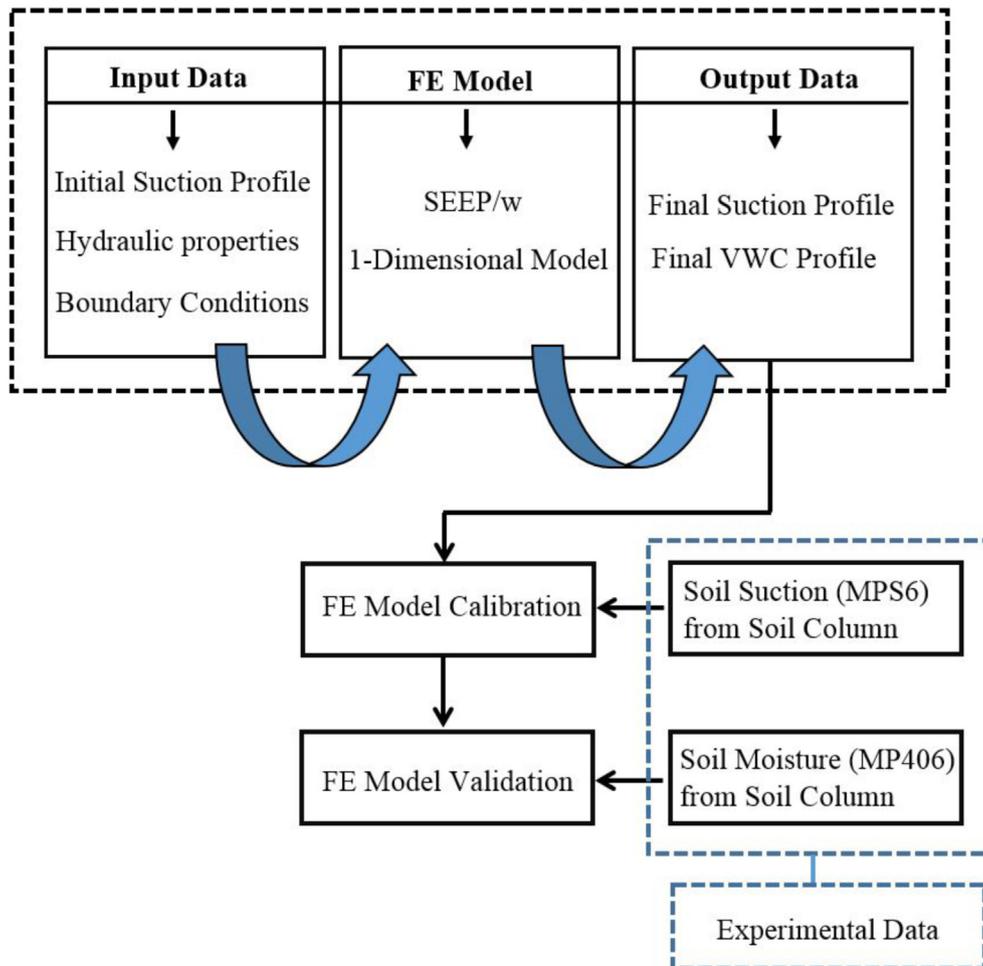


Figure 3. Flow chart of development of the finite element model.

Bulk saturated hydraulic conductivities were introduced to incorporate the effect of the preferential flow paths and boundary effect as discussed in Section 4.1. Therefore, FE model developed using these bulk saturated hydraulic conductivities was calibrated for the soil column.

3.2.2. Boundary conditions

Apart from the hydraulic property functions, hydraulic boundaries are required to model the unsaturated expansive soil behaviour. The climate-ground boundary has always been considered as very complex in field conditions. Recently, many numerical models have reasonably well simulated the field moisture and suction profiles under boundary conditions such as infiltration, evaporation, ponding and runoff (Wilson, 1990; Masia et al., 2004; Rajeev et al., 2012; Li et al., 2016).

A climatic data set comprising of temperature, relative humidity, wind speed, precipitation and potential evaporation, for a selected time span can be input into the FE model. Due to the controlled laboratory conditions and constant head water supply, the water infiltration rate is strictly dependent on the applied pressure head of 0.05 m. The evaporation of ponding water need not to be accounted for due to the constant supply of water from Mariotte's bottle. This simplification allows us to consider only the constant precipitation/flood condition (top hydraulic boundary), instead of complicating the modelling work by incorporation of the environmental parameters such as temperature, humidity, evaporation and wind speed.

To retain the simplicity of FE model, the lateral water flow is logically assumed to be negligible deeming the homogeneity of the soil column. At the initial level of model validation for the wetting process, the influence of micro and macro cracks present on the soil surface is not accounted for. The main reason for this assumption is that soil surface doesn't seem to be cracked at the initial gravimetric water content of 15% and further, during the wetting the micro cracks will be closed due to soil heaving phenomenon. The bottom boundary condition is applied as a drainage boundary in order to prevent air entrapment during the wetting process by opening up to the atmosphere. Compression of entrapped air during the wetting process would be significant during water infiltration since the experiment commenced in an unsaturated condition. After the wetting front reached the full column length of 1.0 m, the constant head was maintained at the bottom of the soil column by introducing a Mariotte's bottle at the bottom as shown in Figure 4.

3.2.3. Initial conditions

Initial soil suction profile for the model was developed based on the MPS6 suction data after equilibrium with the soil in contact. Instrumented soil column was left for 6 days period in order to obtain the desired equilibration of the suction sensors. The actual suction profile data was input to FEM as activation pore water pressure function. Soil suction values are considered as negative pore pressures; hence the initial conditions are fed into the program as negative pressure values.

In this model, adaptive time-stepping is enabled, and the initial increment size was set to 1 min throughout the transient coupled analysis. For a better comparison with the actual results, selected set of time values were entered into the time step control menu.

4. Results & discussion

This section is based on the model calibration by introducing corrected bulk hydraulic conductivities and the comparison of the results obtained from the instrumented soil column and 1-D finite element model developed using SEEP/w. Section 4.1 elaborates on the verification of the bulk hydraulic conductivities for the FE model. Section 4.2 compares and discusses the soil suction results obtained from the physical and FE models. Finally, volumetric water content profile results of the physical and FE models are presented in section 4.3 accompanied by a valid model rectification process to account for the entrapped air in expansive soils under wetting phenomenon.

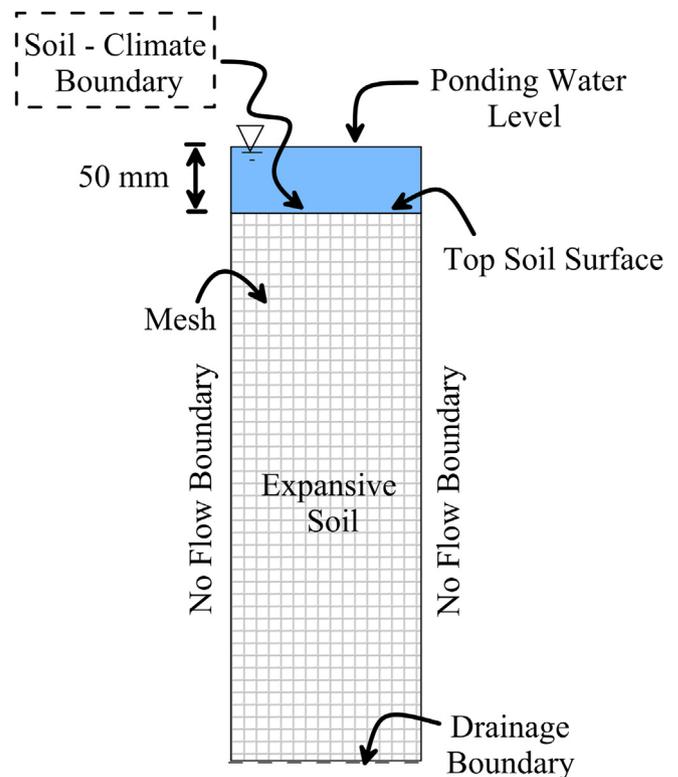


Figure 4. Schematic diagram of the finite element model.

4.1. Determination of bulk hydraulic conductivities

The derived soil hydraulic conductivity function of grey Vertosol was insufficient to model the suction and volumetric water content profiles of the actual soil column. The main reason behind this might be due to the preferential flow paths (Flury et al., 1994) which need to be accounted for when defining the hydraulic conductivity function of grey Vertosols. Therefore, more representative hydraulic conductivity function (i.e. equivalent function to account for soil hydraulic conductivity and preferential flow paths) is important to calibrate the preliminary model. The modified saturated hydraulic conductivity (saturated bulk hydraulic conductivity) for each layer was ascertained by keeping the soil water retention characteristics constant throughout the soil column and varying the saturated hydraulic conductivity for a particular layer until the temporal distribution of suction profiles of the physical model and FE model provides the best fit as shown in Figure 5. The resultant bulk hydraulic conductivity values used for each soil layer is shown in Table 3.

4.2. Comparison of the experimental and numerical results of suction

This section presents the experimental observations of water content and suction profiles with the seepage model predictions. The physical model (soil column) acquired the hydro-mechanical responses in expansive soil stratum for 160 days until the setup reaches the steady-state condition. From the experimental observations, the foremost variations in suction and moisture occurred during the first day of wetting. For the clarity of the explanation, only 3 elapsed time values are illustrated in the results section.

Figure 6 shows the temporal variation of the experimental and numerically modelled suction profiles. Elapsed time values of interest are 0 min, 100 min and 500 min to capture the prime variations of the experimentally obtained and model predicted suction values. Only three time values are selected for the clarity of the illustration purposes.

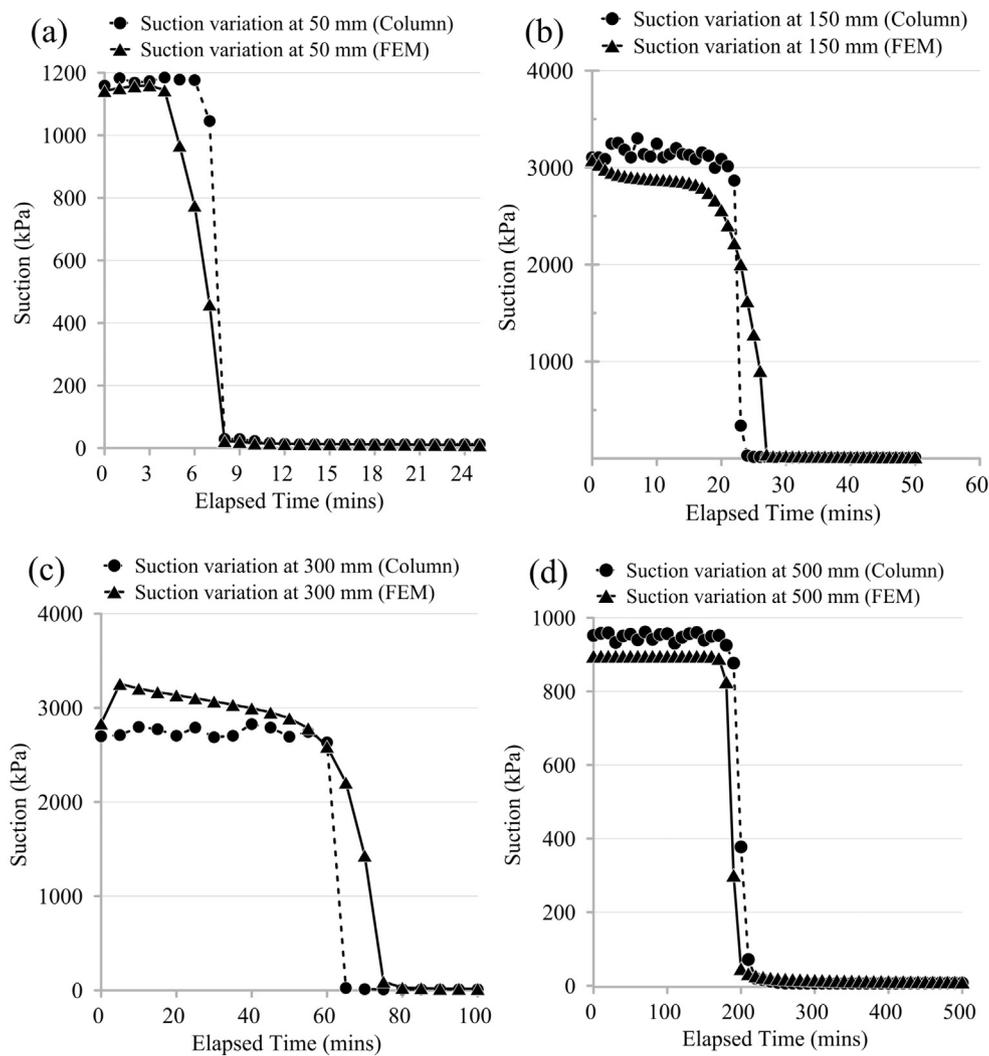


Figure 5. Temporal variation of soil suction at different levels (a) 50 mm depth (b) 150 mm depth (c) 300 mm depth (d) 500 mm depth.

Initial suction profile of FEM at $t = 0$ min depicts an exact match with the corresponding experimental suction profile. The initial experimental soil suction profile was fed into the model as the initial soil condition and that resulted in an exact match with model predictions. Nevertheless, from there onward temporal variations of the model predicted the suction profile a very close match with the experimental observations from the soil column. The difference of the suctions observed at 50 mm level at $t = 100$ min could be due to the insufficient contact of the suction sensor with surrounding soil volume (Cui et al., 2008, 2013; Tang et al., 2009; Schanz et al., 2013; Ng et al., 2016; Gallage et al., 2017). When setting-up the soil column, special care was taken by the authors to make sure better soil to sensor contact. The saturated MPS6 suction sensors were completely covered by the test soil (grey Vertosol) prior to placement on

the subsoil surface and compaction to the desired density. Hence, the observed variation between the actual and predicted suction can be considered minimal.

Suction profiles after $t = 500$ min depict a good agreement with an acceptable deviation of less than 3 kPa at depths to 800 mm. This variation can be considered as a tolerable error of the calibrated FE model. The suction profile observed at 100 min time value was shifted to the left side 500 min from the commencement of the experiment. After 500 min time value, the wetting front was reached up to the 500 mm level resulted in the left shift of the suction profile. This was accurately captured by the developed FE model.

Overall experimental and modelled suction values demonstrate a reduction of the temporal variation in suction with the soil depth. This kind of behaviour is expected from expansive clay soils when wetting fronts infiltrate into the soil from the surface. In a physical soil column setup, water can be infiltrated from the boundary between soil and acrylic, which is known as the boundary effect. The large instrumented soil column used in this experiment minimizes the boundary effect due to the larger surface area (diameter = 0.4 m). However, the model predictions include the rectification for the boundary effect and preferential flow paths, incorporated from the bulk hydraulic conductivity values. Therefore, the developed 1-dimensional seepage model provides an acceptable match with the laboratory observed soil suction profile.

Table 3. Modified bulk hydraulic conductivities.

Soil Depth	Modified Hydraulic Conductivity (m/s)
0 mm–50 mm	6.9×10^{-7}
50 mm–150 mm	2.1×10^{-6}
150 mm–300 mm	2.3×10^{-6}
300 mm–800 mm	5.8×10^{-7}
800 mm–1000 mm	1.2×10^{-8}

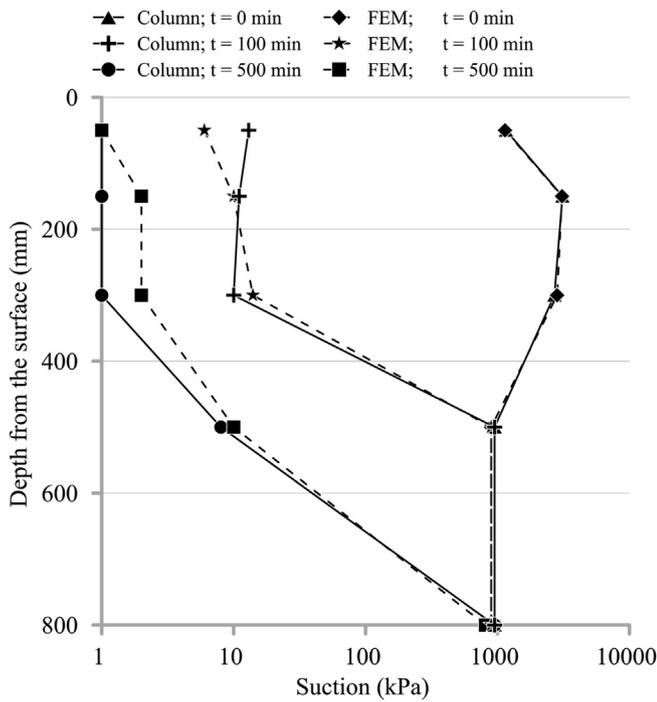


Figure 6. Comparison of instrumented soil column and FEM soil suction data.

4.3. Comparison of the experimental and numerical results of water content

Comparison of temporal variation of experimental and model water content profiles is an important output of this soil column study. Figure 7 shows the temporal variation of the experimentally observed and model-

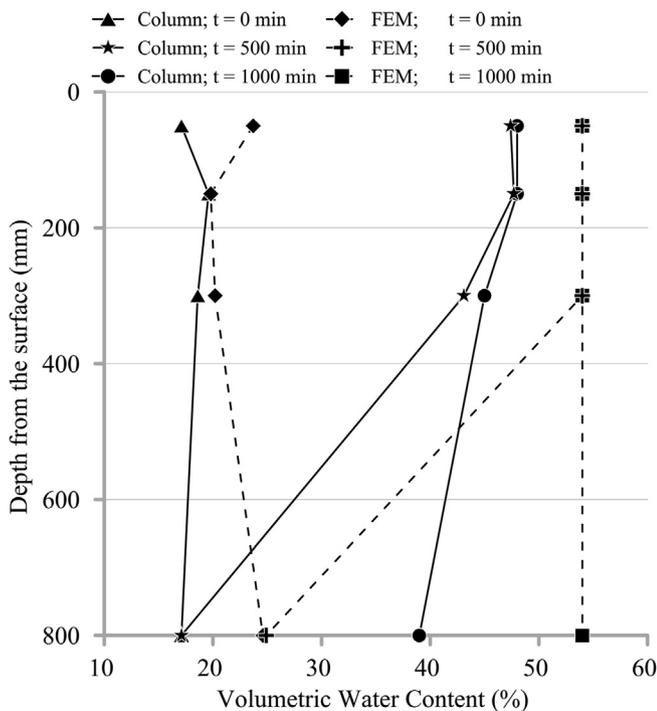


Figure 7. Comparison of instrumented soil column and FEM water content profiles.

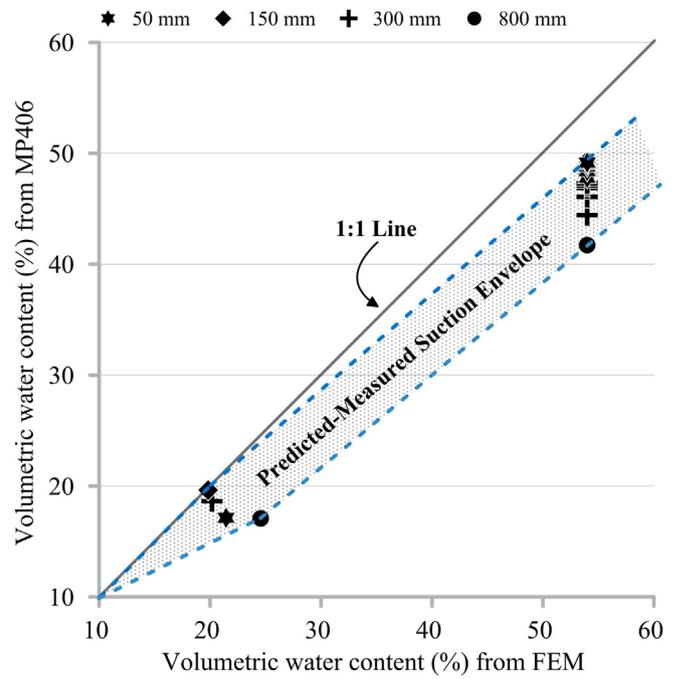


Figure 8. Comparison of measured and predicted VWC.

predicted soil water content profiles. For clarification purposes only 3 elapsed time values; 0 min, 500 min and 1000 min, are selected.

Experimental volumetric water content profile at $t = 0$ min has a good match with the profile generated by the finite element model accompanied with clear overestimations at 50 mm and 800 mm soil depth levels. Experimental moisture profile at 500 min time value depicted a clear right shift of the moisture profile from $t = 0$ min, due to the infiltration of waterfront up to 800 mm level. However, this variation of moisture profile was not accurately captured by the seepage model developed using SEEP/w. Finally, at $t = 1000$ min, the difference between the actual

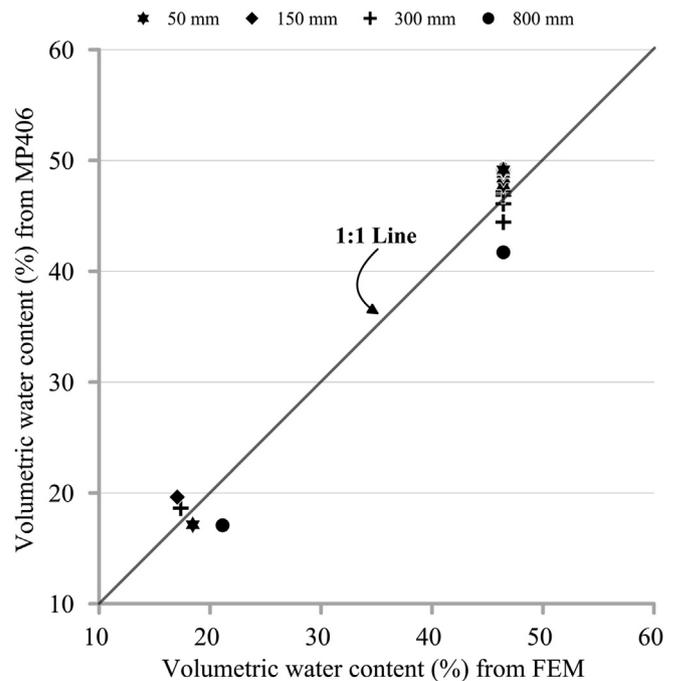


Figure 9. Validation of FEM based on MP406 water content data after incorporation of correction factor.

and the model predicted water content profile becomes greater, specifically at 800 mm depth.

Overall, model predictions overestimate the experimental water content values at all depths. The difference between the model-predicted and experimental volumetric water content becomes greater with the depth. Model predictions and measured values were compatible up to 300 mm depth whereas a very clear difference can be observed at 800 mm level. The main explanation for the difference could be the effect of the entrapped air during the wetting process (Siemens et al., 2014). The effect of entrapped air has always been a complication in soil model setups and to minimize that a free drainage boundary was maintained throughout the complete wetting of soil column.

However, the final water content profile showed a clear variation to the model potentially due to the entrapped air phenomenon. This is expected to be overcome with continuous wetting-drying cycles. A complete shift of the experimental VWC by incorporating a correction factor would provide a very good match with the modelled water content values. This correction factor is incorporated for the predicted data to overcome the effect of 'entrapped air' and preferential flow paths for grey Vertosol soils.

Validation of the developed finite element model can be conducted based on a comparison of the experimental (MP406 responses) and modelled volumetric water content (FEM) values during the wetting process. Comparison of the water content values are presented as a temporal distribution in Figure 8. Model predictions are slightly (11.6%) away from 1:1 agreement with MP406 measured values. Hence, an appropriate correction factor can be used to rectify the overestimation of experimental data. The incorporation of a correction factor for model predictions can be carried out by multiplying all the model predictions by a factor of 0.86. The corrected FEM predictions and measured VWC values then provide a very good match as depicted in Figure 9.

5. Conclusion

Expansive soil responses under wetting climatic condition subsequent to a dry spell has always been critical to investigate for geotechnical engineers. Serious repercussions such as structural flaws (cracking of building materials) can be related to the light-weight structures that are built on these expansive soils. Grey Vertosol is an expansive soil that is abundant in Queensland and Australia, and limited research has been carried out to investigate its responses to extreme climate conditions.

In this study, the authors developed a finite element model (FEM) to replicate the soil suction and moisture responses of 1m high instrumented soil column. Soil water content and suction profiles, and temporal distributions of them were monitored to investigate the hydraulic behaviour of grey Vertosol under known conditions. This instrumented soil column data was then used to model the expansive soil responses under constant head wetting, in terms of suction and volumetric water content profiles.

In this study, the effect of the preferential flow paths has been a concern and was sufficiently addressed by using the knowledge of the temporal variation of soil suction profile. Modelled soil suction profiles at initial and final stages depict good agreement with the experimental results observed in the physical model (instrumented soil column). Further, volumetric water content profiles at initial stage show good agreement with the experimental observations; however, there is a clear difference in volumetric water content at the final stage. The main reason for the difference between experimental and modelled values could be due to the 'entrapped air' during the wetting process. A correction factor (for example, 0.86 for grey Vertosol) incorporated in the model predicted data provides very good agreement with the measured values.

Overall, this study presents a practical approach to numerically model the hydraulic responses of grey Vertosols in a soil column (laboratory physical model tests) under wetting phenomenon. The developed finite element model is in good agreement with data measured from the physical model; hence, can be used to predict the temporal behaviour of suction and volumetric water content profiles of grey Vertosol under laboratory environment.

Declarations

Author contribution statement

Rajitha Shehan Udakumburage, Chaminda Gallage, Les Dawes & Yilin Gui: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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References

- Abeykoon, A.M., Udakumburage, R.S., Gallage, C., Uchimura, T., 2017. Comparison of direct and indirect measured soil-water characteristic curves for a silty sand. *Int. J. GEOMATE* 13 (39), 9–16.
- Adem, H.H., Vanapalli, S.K., 2013. Constitutive modeling approach for estimating 1-D heave with respect to time for expansive soils. *Int. J. Geotech. Eng.* 7 (2), 199–204.
- Aitchison, G.D., Peter, P., 1973. Quantitative description of the stress deformation behaviour of expansive soils. In: 3rd International Conference on Expansive Soils, Haifa, Israel.
- Al-Shamrani, M.A., Abdullah, I.A., 1999. Prediction of potential vertical swell of expansive soils using a triaxial stress path cell. *Q. J. Eng. Geol. Hydrogeol.* 32 (1), 45–54.
- AS 1289.3. 6.3, 2003. Methods of testing soils for engineering purposes—soil classification tests—determination of the particle size distribution of a soil-Standard method of fine analysis using hydrometer. SAI Global.
- AS 1289.3.5.1, 2006. -Methods of Testing Soils for Engineering Purposes—Soil Classification Tests—Determination of the Soil Particle Density of a Soil-Standard Method.
- AS 1289.3.4.1, 2008. (R2016) - Methods of Testing Soils for Engineering Purposes—Soil Classification Tests—Determination of the Linear Shrinkage of a Soil-Standard Method.
- AS 1289.3.1.1, 2009. (R2017)-Methods of Testing Soils for Engineering Purposes—Soil Classification Tests—Determination of the Liquid Limit of a Soil-Four point Casagrande Method.
- AS 1289.3.2.1, 2009. Methods of testing soils for engineering purposes—soil classification tests—determination of the plastic limit of a soil-Standard method. SAI Global.
- AS 1289.3. 6.1, 2009. Methods of testing soils for engineering purposes—soil classification tests—determination of the particle size distribution of a soil-Standard method of analysis by sieving. SAI Global.
- AS 2870, 2011. - Residential Slabs and Footings SAI Global.

- Barbour, S.L., 1998. Nineteenth Canadian Geotechnical Colloquium: the soil-water characteristic curve: a historical perspective. *Can. Geotech. J.* 35 (5), 873–894.
- Benson, C.H., 2007. Modeling unsaturated flow and atmospheric interactions. In: *Theoretical and Numerical Unsaturated Soil Mechanics*. Springer, pp. 187–201.
- Briaud, J.L., Xiong, Z., Sangho, M., 2003. “Shrink test–water content method for shrink and swell predictions”. *J. Geotech. Geoenviron. Eng.* 129 (7), 590–600.
- Chan, D., Gallage, C., Rajeev, P., Kodikara, J., 2015. Field performance of in-service cast iron water reticulation pipe buried in reactive clay. *Can. Geotech. J.* 52 (11), 1861–1873.
- Cheng, Y., Huang, X., Li, C., et al., 2017. “Field and numerical investigation of soil–atmosphere interaction at Nairobi, Kenya”. *Eur. J. Environ. Civil Eng.* 21 (11), 1326–1340.
- Costa, S., Kodikara, J., Cherukuvada, M., 2014. Preliminary modelling of hydro-thermal behaviour of ground reactive zone due to climate change. In: *7th International Congress on Environmental Geotechnics: Iceg2014*. Engineers Australia, p. 895.
- Cui, Y.J., Ta, A.N., Hemmati, S., et al., 2013. Experimental and numerical investigation of soil–atmosphere interaction. *Eng. Geol.* 165, 20–28.
- Cui, Y.J., Tang, A., Mantho, A., et al., 2008. Monitoring Field Soil Suction Using a Miniature Tensiometer.
- Day, R.W., 1994. Swell-shrink behavior of compacted clay. *J. Geotech. Eng.* 120 (3), 618–623.
- Fityus, S.G., Cameron, D.A., Walsh, P.F., 2005. The shrink swell test. *Geotech. Test J.* 28 (1), 1–10.
- Fityus, S.G., Smith, D.W., Allman, M.A., 2004. Expansive soil test site near Newcastle. *J. Geotech. Geoenviron. Eng.* 130 (7), 686–695.
- Flury, M., Flühler, H., Jury, W.A., et al., 1994. Susceptibility of soils to preferential flow of water: a field study. *Water Resour. Res.* 30 (7), 1945–1954.
- Fredlund, D.G., Xing, A., 1994. Equations for the soil-water characteristic curve. *Can. Geotech. J.* 31 (4), 521–532.
- Fredlund, D.G., Xing, A., Huang, S., 1994. Predicting the permeability function for unsaturated soils using the soil-water characteristic curve. *Can. Geotech. J.* 31 (4), 533–546.
- Fredlund, D.G., 2002. Use of soil water characteristic curve in the implementation of unsaturated soil mechanics. In: *Proceedings of the 3rd International Conference on Unsaturated Soils*. Recife, Brazil, pp. 20–23.
- Gallage, C., Chan, D., Gould, S., Kodikara, J., 2009. Behaviour of an in-service cast iron water reticulation pipe buried in expansive soil. In: *OzWater’09 Conference Proceedings*, pp. 1–8.
- Gallage, C., Tehrani, K., Williams, D., 2017. Instrumented large soil-column to investigate climate-induced ground deformation in expansive soil. In: *Proceedings of the 19th International Conference on Soil Mechanics and Geotechnical Engineering*, Seoul 2017, pp. 1147–1150.
- Gao, Y., Sun, D., Wu, Y., 2017. Volume change behaviour of unsaturated compacted weakly expansive soils. *Bull. Eng. Geol. Environ.* 1–12.
- Gitirana Jr., G., Fredlund, D.G., Fredlund, M.D., 2005. Infiltration-runoff boundary conditions in seepage analysis. *Sat* 1, 3.
- Gitirana Jr., G., Fredlund, M.D., Fredlund, D.G., 2006. Numerical modelling of soil–atmosphere interaction for unsaturated surfaces. In: *Geotechnical Special Publication*, pp. 658–669.
- Hu, Y., Azam, S., 2008. Instrumentation for field monitoring in expansive soils. In: *61st Canadian Geotechnical Conference*, Edmonton, Canada.
- Ito, M., Azam, S., 2010. Determination of swelling and shrinkage properties of undisturbed expansive soils. *Geotech. Geol. Eng.* 28 (4), 413–422.
- Ito, M., Azam, S., Hu, Y., 2014. A two stage model for moisture-induced deformations in expansive soils. *Environ. Syst. Res.* 3 (1), 19.
- Ito, M., Hu, Y., 2011. Prediction of the behaviour of expansive soils. In: *Proceedings, 64 Th Canadian Geotechnical Conference and 14th Pan-American Conference on Soil Mechanics and Geotechnical Engineering*, pp. 2–6.
- Karunaratne, A.M.A.N., Sivanerupam, S., Gad, E.F., et al., 2014. Field and laboratory investigation of an expansive soil site in Melbourne. *Aust. Geomech J.* 49 (2), 85–94.
- Karunaratne, A.M.A.N., Fardipour, M., Gad, E.F., et al., 2018. Modelling of climate induced moisture variations and subsequent ground movements in expansive soils. *Geotech. Geol. Eng.* 36 (4), 2455–2477.
- Khan, Md, Jay, A., Wang, X., et al., 2017. A study of the swell-shrink behavior of expansive Moreland clay. *Int. J. Geotech. Eng.* 1–13.
- Li, P., Li, T., Vanapalli, S.K., 2016. Influence of environmental factors on the wetting front depth: a case study in the Loess Plateau. *Eng. Geol.* 214, 1–10.
- Masia, M.J., Totoev, Y.Z., Kleeman, P.W., 2004. Modeling expansive soil movements beneath structures. *J. Geotech. Geoenviron. Eng.* 130 (6), 572–579.
- Nelson, J.D., 2015. Time dependence of swelling in oedometer tests on expansive soil. In: *15th Asian Regional Conference on Soil Mechanics and Geotechnical Engineering, ARC 2015: New Innovations and Sustainability*, pp. 490–493.
- Ng, C.W.W., Zhan, L.T., 2007. Comparative study of rainfall infiltration into a bare and a grassed unsaturated expansive soil slope. *Soils Found.* 47 (2), 207–217.
- Ng, C.W.W., Coo, J.L., Chen, Z.K., et al., 2016. Water infiltration into a new three-layer landfill cover system. *J. Environ. Eng.* 142 (5), 04016007.
- Rajeev, P., Chan, D., Kodikara, J., 2012. “Ground–atmosphere interaction modelling for long-term prediction of soil moisture and temperature”. *Can. Geotech. J.* 49 (9), 1059–1073.
- Rao, A.S., Phanikumar, B.R., Sharma, R.S., 2004. Prediction of swelling characteristics of remoulded and compacted expansive soils using free swell index. *Q. J. Eng. Geol. Hydrogeol.* 37 (3), 217–226.
- Schanz, T., Nguyen-Tuan, L., Datcheva, M., 2013. A column experiment to study the thermo-hydro-mechanical behaviour of expansive soils. *Rock Mech. Rock Eng.* 46 (6), 1287–1301.
- Siemens, G.A., Take, W.A., Peters, S.B., 2014. Physical and numerical modeling of infiltration including consideration of the pore-air phase. *Can. Geotech. J.* 51 (12), 1475–1487.
- Tang, A.M.A.N.T., Cui, Y.J., Thiriat, J., 2009. Development of a large-scale infiltration tank for determination of the hydraulic properties of expansive clays. *Geotech. Test J.* 32 (5).
- Udukumburage, R.S., Gallage, C., Dawes, L., 2018. Loaded swell tests to estimate the heave of the expansive soil in instrumented soil column. In: *8th International Conference on Geotechnique, Construction Materials and Environment*. The Geomate International Society, Kuala Lumpur, Malaysia, pp. 390–395.
- Udukumburage, R.S., Gallage, C., Dawes, L., 2019a. Investigation of the effect of initial water content and surcharge on volume change behaviour of compacted grey Vertosol. In: *13th Australia Newzealand Conference on Geomechanics*. Australian Geomechanics Society, Sydney, Australia, pp. 1029–1034.
- Udukumburage, R.S., Gallage, C., Dawes, L., 2019b. Oedometer based estimation of vertical shrinkage of expansive soil in a large instrumented soil column. *Heliyon* 5 (9), e02380.
- Udukumburage, R.S., Gallage, C., Dawes, L., 2020. An instrumented large soil column to investigate climatic ground interaction. *Int. J. Phys. Model. Geotech.* 1–17.
- Wilson, G.W., 1990. “Soil Evaporative Fluxes for Geotechnical Engineering Problems”. PhD Dissertation. University of Saskatchewan.