Method Article

Soil pedostructure-based method for calculating the soil-water holding properties

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ABSTRACT

Soil aggregates structure (pedostructure) plays a pivotal role in regulating water and nutrient circulation, and consequently defines soil health, productivity, and water use efficiency. However, the soil aggregates structure is not currently considered in the quantification of soil-water holding properties. The authors applied a thermodynamic and soil structure-based approach to quantify soil-water holding properties. The paper provides a methodology, based on pedostructure concept, to quantify field capacity (FC), permanent wilting point (PWP), and available water (AW). The validity of the developed method was tested through application to two types of soil: a loamy fine sand soil and a silt loam soil. The calculated values for FC, PWP, and AW were compared with the FAO recommended values of FC, PWP and AW. For the loamy fine sand, the calculated values were: FC = 0.208 m³/m³, PWP = 0.068 m³/m³, and AW = 0.140 m³/m³ all of which fall within the recommended values of FAO for such a soil type. Similarly, the calculated values for the silt loam were: FC = 0.283 m³/m³, PWP = 0.184 m³/m³, and AW = 0.071 m³/m³ all were in agreement with the FAO recommended ranges for such a soil type.

- A thermodynamic, structure-based approach for soil water holding properties.
- Unique solutions for quantifying both field capacity and permanent wilting point.

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Method details

This work introduces a new methodology for calculating the field capacity (FC), Permanent Wilting Point (PWP), and available (AW), using the soil aggregates structure (pedostructure) instead of soil texture. The Pedostructure approach was developed from the pedological description of the level of soil aggregates organization in which the primary particles (minerals “sand, silt, clay” and natural organic matter) assemble to form “primary” peds. These primary peds then aggregate to form the pedostructure (soil aggregates structure) as described by Braudeau et al. [1]. Pedostructure can be practically taken using a standard soil core (Fig. 1a) to represent the unique soil organization of the horizon from which it was taken. Each soil type has a unique pedostructure whose hydro-structural properties (pore systems and potential energies of surface charges on the primary peds) can be described using various hydrostructural parameters [2]. These parameters are extracted from the continuously and simultaneously measured data points of the water retention curve (WRC: the curve of soil water content vs. soil suction) and soil shrinkage curve (ShC: the relationship between the soil water content and the soil volume) produced by the TypoSoil™ device (Fig. 2a).

According to the thermodynamic formulation of the WRC and the ShC [2], one should recognize that there are two pore regions within a pedostructure (Fig. 2b):

1 Micro-pore region, representing the pore volume and structure inside the primary peds. Its water content is called micro-water content ($W_{mi}$). The following characteristic points of micro-pore water content are unique for each soil type (Fig. 1b): $W_M$ is the water content equivalent to the

![Standard Soil Core](image)

Fig. 1. Pedostructure concept: (a) a standard soil core to represent the pedostructure of a soil horizon, (b) delineating the two water types of a pedostructure by soil shrinkage curve (ShC) and water retention curve. On the ShC, points (A, N, B, C, M, D, E, L, and F) are the characteristic points of the water pools of the different shrinkage phases: interpedal, structural, basic and residual.
Materials and methods

This work builds on the work of Assi et al. [3] and Braudeau et al. [2] to develop a methodology for calculating the FC, PWP, and AW.

Part 1: soil samples collection, preparation, and characterization

Note: the procedures mentioned hereafter have been well described in previous peer-reviewed papers [2,3], a book [4], and a user manual [5]. Spreadsheets are available to treat the data obtained from the TypoSoil™ and will be provided as supplementary material to this paper. This section presents the steps to be done and references the published work for more details.

1 Collect the soil samples. Standard cylindrical stainless-steel soil cores (Φ = 5 cm, h = 5 cm) are used to collect the soil samples from the field. Each soil sample represents the peds of the soil horizon from which it was taken. In this study, two soil types were sampled, and soil samples were taken from the top horizon. The soil types are: (1) Chazos loamy fine sand soil, an Alfisol, from College Station, TX, USA, with a texture of: 4% clay, 13% silt, and 83% sand; and (2) Sabkha silt loam soil, an Aridisol, from Al Khor, Qatar, with a texture of: 15% clay, 65% silt, and 20% sand.

2 Prepare the soil samples for TypoSoil™ measurement (Fig. 2a). TypoSoil™ [6] provides continuous and simultaneous measurement of three state variables for 8 soil samples in each run (Table 1): moisture content (measured by a balance “MASSE”), soil suction (measured by ceramic cup tensiometers “TENSIO”), and specific volume (measured by two laser beams “BARR 1 and BARR 2”, and 1 laser spot “SPOT”). These state variables will be used to construct the WRC and ShC. The
Fig. 3. Pesostructure water contents: (a) characteristic points of the pesostructure water contents and the corresponding soil-water holding properties; (b) modeling the pesostructure water contents from saturation to dry state. This thermodynamic and structure-based modeling identifies the efficient contribution of the different water pore systems as a respond of soil-water loss, and thus it can be used to identify the water-holding characteristic properties of a specific soil type and soil horizon.
Table 1
TypoSoil™ raw data.

| Slot | Code      | Date          | Batch       | Operator | GenDate       |
|------|-----------|---------------|-------------|----------|---------------|
|      | RR LOC2 UD| 25/7/2013 – 8 h 31 | TYPO130725 | Josh     | 20130728 - 093755 |

| "Entetes" | "TEMPS" | "BARR1" | "BARR2" | "SPOT" | "MASSE" | "TENSIO" |
|-----------|---------|---------|---------|--------|---------|---------|
| Data      | 79      | 0       | 856     | 1156   | 187.54  | 1934    |
| Data      | 658     | 709     | 198     | 1185   | 187.29  | 1931    |
| Data      | 1227    | 708     | 202     | 1183   | 187.13  | 1930    |

\[
\mathcal{V} = \frac{\pi D^2 H}{4M_s} \times 10^{-4}
\]

where, \( \mathcal{V} \) is the specific volume of the soil sample [dm\(^3\) kg\(^{-1}\) solid], \( D \) and \( H \) are, respectively, the measured diameter and height of the soil sample by the laser sensors [dm], \( M_s \) is the dry mass of the soil sample at 105 °C [kg solid].

- The water retention curve (WRC) is constructed by drawing the calculated soil water content \( (W_{\text{water}}\text{kg}^{-1}\text{solid}) \) vs. the measured soil suction \( (h \text{ [dm} \sim \text{kPa}]) \).
- The soil shrinkage curve (ShC) is constructed by drawing the calculated soil water content \( (W_{\text{water}}\text{kg}^{-1}\text{solid}) \) vs. the calculated specific volume \( \mathcal{V} \text{ [dm}^3\text{Kg}^{-1}\text{solid}]. \)
- Extract the characteristic parameters of the pedostructure (Fig. 2b, c) by adjusting the thermodynamic equations of WRC and ShC [2] with the measured ones by TypoSoil™. Again, the procedures of extracting these parameters were explained in Assi et al. [3] and chapter 6 of Braudeau et al., [4].
- Model the pedostructure water contents (Fig. 3). The spreadsheets will then use these extracted parameters to calculate the different pedostructure water contents: interpedal water content \( (W_{ip}) \) (Eq. 3); macro-pore water content \( (W_{ma})(\text{Eq. } 4) \), micro-pore water content \( (W_{mi})(\text{Eq. } 5) \), basic water content \( (w_b) \) (Eq. 6), and residual water content \( (w_r) \) (Eq. 7). These values can be calculated by using the following equations. Table 2 below provides a summary of the state variables, pedostructure water contents and the needed parameters to calculate each of them.

\[
W_{ip} = \frac{1}{k_L} \ln[1 + \exp(k_L(W - W_L))]
\]

\[
W_{ma}^{eq}(W) = \left( W + \frac{E}{A} \right) + \sqrt{\frac{\left( W + \frac{E}{A} \right)^2 - \left( 4\frac{E_{ma}}{A}W \right)}{2}}
\]

\[
W_{mi}^{eq}(W) = W - W_{ma} = \left( W - \frac{E}{A} \right) - \sqrt{\frac{\left( W + \frac{E}{A} \right)^2 - \left( 4\frac{E_{mi}}{A}W \right)}{2}}
\]
Table 2  
The state variables and the corresponding parameters of the pedostructure WRC and ShC.

| Symbol       | Definition                                                                 | Unit                              | Corresponding hydro-structural parameters |
|--------------|---------------------------------------------------------------------------|-----------------------------------|-------------------------------------------|
| $W_{sstr}$   | Pedostructure saturated water content                                      | $k_{sw}^{1}$ $k_{soil}^{-1}$      | $W_{emstr}^{eq}$ $W_{mi}^{eq}$            |
| $W$          | Pedostructure water content                                               | $k_{sw}^{1}$ $k_{soil}^{-1}$      | $E/A, E_{max}/A$                          |
| $W_{eqmi}$   | Micro pore water content of the pedostructure                             | $k_{sw}^{1}$ $k_{soil}^{-1}$      | $F_{ma}, F_{mi}$                          |
| $W_{eqma}$   | Macropore water content of the pedostructure                              | $k_{sw}^{1}$ $k_{soil}^{-1}$      |                                           |
| $h^N(W)$     | Pedostructure water potential which is in instantaneous equilibrium        | $dm \sim kPa$                     |                                           |
| $h_{mi}(W_{eqmi})$ | between inside and outside the primary peds, such that:                    |                                   |                                           |
| $V$          | the specific volume of the pedostructure                                  | $dm^3$ $k_{soil}^{-1}$            |                                           |
| $w_{eq}$     | Specific water content of the water pool associated to the residual linear shrinkage phase of the pedostructure | $k_{sw}^{1}$ $k_{soil}^{-1}$      |                                           |
| $w_{eqbi}$   | Specific water content of the water pool associated to the basic linear shrinkage phase of the pedostructure | $k_{sw}^{1}$ $k_{soil}^{-1}$      |                                           |
| $w_{eqst}$   | Specific water content of the water pool associated to the structural linear shrinkage phase of the pedostructure | $k_{sw}^{1}$ $k_{soil}^{-1}$      |                                           |
| $w_{eqip}$   | Specific water content of the water pool associated to the interpedal linear shrinkage phase of the pedostructure, parallel to the saturation line | $k_{sw}^{1}$ $k_{soil}^{-1}$ $k_L, W_L$ |                                           |

$$w_{bs} = \frac{1}{k_N} \ln\left[1 + \exp(k_N(W_{mi}^{eq} - W_{mi}^{eq}))\right]$$

(6)

$$w_{re} = W - \frac{1}{k_N} \ln\left[1 + \exp(k_N(W - W_{mi}^{eq}))\right]$$

(7)

Where,

- $W$ pedostructure water content excluding the saturated interpedal water $[k_{sw}^{1} k_{soil}^{-1}]$,
- $W_{ma}$ gravimetric macro-pore water content “outside the primary peds” $[k_{sw}^{1} k_{soil}^{-1}]$,
- $W_{mi}$ gravimetric micropore water content “inside the primary peds” $[k_{sw}^{1} k_{soil}^{-1}]$,
- $E_{ma}$ potential energy of surface charges positioned on the outer surface of the clay plasma of the primary peds $[J k_{soil}^{-1}]$,
- $E_{mi}$ potential energy of surface charges positioned inside the clay plasma of the primary peds $[J k_{soil}^{-1}]$,
- $k_N$ and $k_L$ represent the vertical distance between the intersection points of the two tangents at points N, and L (Fig. 1b) and the measured shrinkage curve, respectively $[k_{sw}^{1} k_{soil}^{-1}]$.
- $W_{mi}^{eq}$ micro-pore water content calculated by (Eq. 5) but by using $W_N$ instead of $W$.
- $W_{mi}$ water content at the intersection point (N) in (Fig. 1b) and represents the water content of the primary peds at dry state such that $W_N = \max(w_{re}) [k_{sw}^{1} k_{soil}^{-1}]$.
- $w_{re}$ water pool associated with the residual shrinkage phase of the shrinkage curve $[k_{sw}^{1} k_{soil}^{-1}]$.
- $W_L$ water content at the intersection point (L) (Fig. 1b) such that $W_L = W_M + \max(w_{re}) [k_{sw}^{1} k_{soil}^{-1}]$.
- $W_M$ water content at the intersection point (M) (Fig. 1b) such that $W_M = W_N + \max(w_{bs})$ and it represents the saturated water content of the micropore domain $[k_{sw}^{1} k_{soil}^{-1}]$. 


Part 2: define and calculate the field capacity (FC), permanent wilting point (PWP), and available water (AW) based on the peds

The authors made use of the modelled peds to calculate the field capacity (FC), permanent wilting point (PWP), and available water (AW). These values can be calculated such that:

- **Field capacity** \( (W_{FC}) \): the water content at field capacity corresponds to the water content at which the thermodynamic forces between soil and water are much higher than the gravitational forces to appoint where the water flux out of the soil medium is negligible. Based on the thermodynamic understanding of peds, as explained earlier, this water content can then be identified by the rapid change in the micro-pore water content curve. Therefore, FC of a soil occurs at the maximum of the change in slope of the \( W_{mi} \) curve. This value can be identified by finding the root of the third derivative of \( W_{mi} \) curve, or by numerical solutions (Fig. 4). At this point, all the interpedal water will have vanished.

- **Permanent Wilting Point** \( (W_{PWP}) \): the water content at PWP corresponds to the water content at the air entry point of the micro-pore domain. At this point, a capillary break within the micro-porosity of primary peds occurs and the water cannot be reached by the plant roots at the contact surface of the peds \[9\]. This water content corresponds to point B in Fig. 3. At this point, the soil suction is around pF4.2 (i.e. soil suction: 3791 hPa which is equivalent to 15,000 hPa air pressure as applied in Richards’ apparatus). So, Point B can represent the maximum change in the slope of the residual water content curve \( W_{re} \), as shown in Fig. 3, the soil water content at this maximum change in slope will be used as permanent wilting point.

- **Available Water Capacity** \( (AW) \): available water capacity can be then identified as the difference between the FC and PWP, such that:

\[
AW = W_{FC} - W_{PWP}
\]

- **Unit Conversion**: The calculated soil water holding properties: field capacity, permanent wilting point, and available water are calculated as gravimetric water contents \( (\text{kg}_{\text{water}}/\text{kg}_{\text{soil}}) \). To be able to compare the results with existing methods, the gravimetric water contents as reported in peds need to be converted to volumetric water contents \( (\text{m}^3/\text{m}^3) \). The conversion from gravimetric water content into volumetric water content was done as following:

\[
\theta_{FC} = \frac{W_{FC}}{\rho_{FC}} \left( \frac{\rho_{FC}}{\rho_w} \right)
\]

\[
\theta_{PWP} = \frac{W_{PWP}}{\rho_{PWP}} \left( \frac{\rho_{PWP}}{\rho_w} \right)
\]

where, \( \theta_{FC} \) and \( \theta_{PWP} \) are the volumetric water contents at field capacity and permanent wilting point, respectively \( [\text{m}^3/\text{m}^3] \). \( \rho_{FC} \) and \( \rho_{PWP} \) are the bulk densities of the soil at field capacity and permanent wilting point, respectively \( [\text{kg}_{\text{soil}}/\text{m}^3_{\text{soil}}] \), and \( \rho_w \) is the specific density of water \( [\text{kg}_{\text{water}}/\text{m}^3_{\text{water}}] \). Where \( \rho_{FC} = 1/\rho_{FC} \) and \( \rho_{PWP} = 1/\rho_{PWP} \). Here, \( \rho_{FC} \) and \( \rho_{PWP} \) are the specific volumes at the field capacity and permanent wilting point as observed in the soil shrinkage curve, respectively.
Additional information

There are different approaches and recommended values to estimate the field capacities and permanent wilting points. There are variations in the recommended values, even by the most standard method. These soil-water holding properties are highly affected by the soil structure and soil organic matter. FAO estimation [7] and the Department of Agriculture Bulletin 462 are among the standard and widely used methods for estimating the FC, PWP, and AW values. However, one can observe some noticeable variations between their estimation “recommended” values based on the soil texture. For example, for a silty clay loam soil, FAO suggests a field capacity in a range of 0.300–0.370 m³/m³, whereas, Bulletin 462 suggests an average value of 0.28 m³/m³. One can recognize that the suggested value by Bulletin 462 [8] is outside of the recommend range of values by FAO.

In this paper, the focus was on building a standard methodology for estimating field capacity and permanent wilting point that consider the soil aggregates structure. As shown in Table 3, most of the calculated values for FC and PWP were in good agreement with the recommended values by FAO.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.mex.2018.08.006.

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Table 3
The estimated values of the field capacity (FC), permanent wilting point (PWP) and available water (AW) based on the pedostructure method and the corresponded range of values as recommended by FAO [7].

| Soil Sample       | Pedostructure Method | FAO Method |
|-------------------|----------------------|------------|
|                   | $W_{FC}$ (Kg/kg)     | $\theta_{FC}$ (m$^3$/m$^3$) | $W_{PWP}$ (Kg/kg)  | $\theta_{PWP}$ (m$^3$/m$^3$) | AW (m$^3$/m$^3$) | $\theta_{PWP}$ (m$^3$/m$^3$) | AW (m$^3$/m$^3$) |
| Chazos Soil       | 0.144                | 0.208      | 0.047                | 0.068         | 0.140                  | 0.110–0.190 | 0.030–0.100 | 0.010–0.160 |
| [Loamy fine sand] |                      |            |                      |               |                       |            |            |            |
| Sabkha Soil       | 0.247                | 0.283      | 0.212                | 0.184         | 0.071                  | 0.220–0.360 | 0.090–0.210 | 0.010–0.270 |
| [Silt loam]       |                      |            |                      |               |                       |            |            |            |

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