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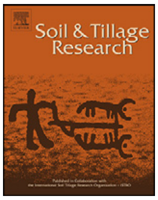

Are standard values the best choice? A critical statement on rheological soil fluid properties viscosity and surface tension

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ABSTRACT

The rheological properties of a fluid in terms of viscosity η and surface tension γ are often neglected in studies on hydrostatic and hydrodynamic phenomena. However, their measurement seems to provide us with more benefit than it takes time and effort. Especially regarding transport of fluids in soil, the exact definition of the fluid properties is necessary for predicting water transport correctly.

In this paper we review and summarize the available scientific knowledge on rheological soil fluid properties and supplement it with our own investigations on viscosity and surface tension of salt and soil solutions. Our results showed neither a clear linear relationship between η and salt concentration in aqueous solutions nor to the kind of cation or anion of the dissolved salt whereas the surface tension of salt solutions generally increased linearly with molar concentration though at different rates. As an example, a 1 M $MgSO_4$ solution doubled η but increased γ only by 3%, whereas 1 M $MgCl_2$ caused 4% increase in γ, but still 50% increase in η. Viscosity of soil solutions depended on soil–water ratio as well as fertilization of the soil. The largest deviation to standard η of water was about 6% at 40% gravimetric water content.

Concluding from the literature review and our own findings, we recommend to additionally measure rheology (namely viscosity and surface tension) of the soil solution in order to improve modeling of hydrostatic and hydrodynamic phenomena in soils by utilizing more realistic fluid properties which might deviate significantly from the usually employed standard values. The mathematical error cumulates with increasing salt concentration as a deviation of 10% to the standard value also causes an error of 10% in linear relationships derived from that parameter, e.g. the equation of Hagen–Poiseuille.

Future investigations should focus on the manifold single effects as well as on the interactions of different dissolved components in the soil solution on viscosity and surface tension and how these are influenced by temperature, pressure (i.e. shear rate) and concentration.

1. Soil fluid properties in soil science

1.1. Actual provision for rheological dynamics in soil science

Soil science in general focuses on the chemical properties of soil fluids, i.e. its composition and concentration of various salts, colloids and dissolved molecules. There is no doubt that changes of those properties also alter the fluid's behavior, especially in terms of rheology, e.g. its viscosity. The viscosity denotes the ability of a fluid to flow such that low values are attributed to easily flowing and high values to pasty substances. It is commonly stated that salts increase the viscosity of pure water. Abdulagatov and Azizov (2008) investigated the viscosity of potassium (K) bromide solutions in dependence of temperature and salt concentration, and Chenlo et al. (1997) observed interactions between iron (Fe) sulfate solutions with K sulfate and K chloride affecting viscosity. Apart from salts or, more precisely, ions, polysaccharides are present in all soils containing organic matter. Their rheological properties were analyzed among others by Hoorfar et al. (2006), Matia-Merino et al. (2012) and Stokke et al. (1992). Stojilkovic et al. (2003) even found a possibility to relate electrical conductivity of a solution to its viscosity. Though for many single substances in aqueous solution the intrinsic dependency of viscosity on temperature was proven (Viswanath and Natarajan, 1989), a clear verification of Newtonian behavior (i.e. linear relationship of viscosity and temperature) for many salts in aqueous solution is still missing. Nakai et al. (1997) stated that the viscosity of aqueous solutions of K chloride varies with temperature and pressure which

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was observed for water already some time ago (D'Ans and Lax, 1967, cit. in Hartge and Horn, 1999).

Besides the viscosity, also other fluid properties can be expected to change due to an altered soil solution composition, e.g. surface tension. The surface tension denotes the energy required to enlarge the surface of a fluid (given in mJ m^{-2} or mN m^{-1}, respectively). Investigations by Hoorfar et al. (2006) confirmed an increase in surface tension due to K chloride; however, they detected a tension-decreasing impact of polysaccharides although generally polysaccharides are thought to increase surface tension (cf. Docoslis et al., 2000). The ability of a fluid to wet a surface, i.e. the wettability, further depends on the surface itself. With regard to soil, the wettability was determined in lots of studies via the contact angle or measurements of sorptivity (among others Bauters et al., 2000; Callies and Quere, 2005; Doerr et al., 2007; Hallett, 2008). Soils are known to develop hydrophobicity especially dependent on water content (Dekker et al., 1998) and soil organic matter (Chenu et al., 2000), e.g. by mucilage (Czarnes et al., 2000) or biological exudates. The latter were investigated via analogue substances by Peng et al. (2011). The impact of reduced wettability on other soil properties is mainly taken into account with regard to an increased aggregate stability (as the risk of slaking decreases) (Chenu et al., 2000; Zhang and Hartge, 1992), but usually ignored when determining e.g. pore size distribution from water retention functions. The examinations by Goebel et al. (2005) emphasize those interactions and found a decreasing surface tension due to the fact that ethanol reduced aggregate breakdown in comparison to water. Aggregate stability, however, is of large importance for the bulk soil stability and the accessibility of nutrients and soil organic matter. Hence, for the wettability of a soil, it is of similar importance to know the surface tension of the wetting fluid (i.e. the interface tension of liquid to air) as the interface tension of solid to liquid phase, which is generally determined via the contact angle against a standard fluid (e.g. distilled water).

1.2. Utilization of fluid properties in soil physics

The fluid properties viscosity and surface tension are treated as constants and defined by standard values of pure water, namely a viscosity of 1.00 mPas and surface tension of 72.75 mN m^{-1} at 20 °C. Furthermore, in the (expectable) absence of standard conditions, the error caused by the utilization of standard values is even increased by not considering spatial and temporal dynamic changes of the fluid properties (e.g. seasonal changes or changes related to matric potential).

In soil physics numerous equations for modeling, interpolation and other purposes (e.g. prediction or mathematical derivation of soil physical parameters like pore size distribution) require numerical values for fluid properties. One example is the equation of Hagen–Poiseuille which defines the amount of water percolating through a pore of defined diameter per time unit Q ($cm^3\ s^{-1}$):

$$Q = r^4 \cdot \pi \cdot \Delta p \cdot (8 \cdot \eta \cdot l)^{-1} \tag{1}$$

where r is the pore radius, Δp the driving pressure gradient (Pa), η the viscosity of the transported fluid (Pa s) and l the pore length (cm).

Another parameter is the saturated hydraulic conductivity k_s (m s^{-1}) denoting the soil's conductivity for fluids in a saturated state. The corresponding equation (Eq. (2)) contains both the hydraulic permeability k which denotes the intrinsic permeability as well as the fluid's properties themselves:

$$k_s = k \cdot \rho \cdot g \cdot \eta^{-1} \tag{2}$$

where k denotes the hydraulic permeability (m^2), η the viscosity (Pa s), ρ the density of the fluid (g m^{-3}) and g the gravitational acceleration (9.81 m s^{-2}). Also the Reynold number Re (−) which marks the transgression of laminar to turbulent flow in a pore includes the viscosity:

$$\mathrm{Re} = \rho \cdot v \cdot l \cdot \eta^{-1} \tag{3}$$

where ρ denotes the density of the fluid (g cm^{-3}), v the flow velocity (cm s^{-1}), l the length of the percolated pore (cm) and η the viscosity (Pa s).

The viscosity furthermore appears in Stoke's equation used for the determination of the sinking velocity v of particles (m s^{-1}), where the temperature is generally measured and thus the viscosity corrected for it but not for the absolute viscosity:

$$v = 2 \cdot r^2 \cdot g \cdot (\rho_s - \rho_l) \cdot (9 \cdot \eta)^{-1} \tag{4}$$

where r is the radius of the particle (m), g the gravitational acceleration (9.81 m s^{-2}); ρ_s the density of the particle (g cm^{-3}), ρ_l the density of the fluid (g cm^{-3}) and η the viscosity (Pa s).

Concerning the surface tension of the soil fluid, it is a common parameter needed in soil physics, e.g. for the determination of the capillary rise. It is often considered to be equal to that of pure water although the soil solution never consists of such a purified liquid. The corresponding equation, the Young–Laplace's law, allows calculating the pore diameter of those pores which are still water-filled at a defined matric potential:

$$r = 2 \cdot \gamma \cdot \cos\alpha \cdot (h \cdot \rho \cdot g)^{-1} \tag{5}$$

where r is the radius of the pore (cm), γ the surface tension of the fluid (g s^{-2}), α the contact angle (°), h the height of capillary rise (cm), ρ the density of the fluid (g cm^{-3}) and g denotes the gravitational acceleration (9.81 m s^{-2})

In this equation, the "real" values of another parameter are generally neglected, namely the contact angle α denoting the soil's wettability (°). Especially organic matter induces a lower wettability and thus increasing repellency (see previous chapter), hence a certain degree of hydrophobicity is present in almost all soils containing organic matter and having experienced moderate drying. The contact angle further depends on the surface tension, namely on the tension ratios between the different interfaces (solid to gaseous, solid to fluid, fluid to gaseous phase) where the surface tension denotes the interface tension fluid to gaseous phase, as is described in Young's equation.

$$\cos\alpha = (\gamma_s - \gamma_{sf}) \cdot \gamma_f^{-1} \tag{6}$$

where γ_s denotes the surface tension of the solid–gaseous interface (mN m^{-1}), γ_{sf} the surface tension of the solid–fluid interface (mN m^{-1}) and γ_f the surface tension of the fluid–gaseous interface (mN m^{-1}).

Soils with a contact angle exceeding 90° are classified as repellent or hydrophobic. Generally, the interface tension of water towards air (γ_s) is higher than that towards the soil (the solid, γ_{sf}). Hence, the fluid tends to minimize the interface area of water–air and spread on the soil completely if $\alpha = 0°$. In that case γ_f is equal to the difference of γ_s and γ_{sf}. On the other hand, if $\alpha = 90°$, cos α is 0 and $\gamma_s = \gamma_{sf}$.

1.3. Consequences of the use of standard values for rheological fluid properties

One of the processes influenced by rheological fluid properties is water transport in soil. Especially during loading, hydraulic and mechanical processes interact as e.g. the reallocation of the soil solution in the compressed soil core is not only governed by the soil's pore capacity and architecture but also by the fluid's properties either enhancing or impeding the drainage (Horn, 1993). Examinations of Peth and Horn (2006), Krümmelbein et al. (2008) and Reszkowska et al. (2011) proved that in the wake of