DISCUSSION

Formation and evolution of water menisci in unsaturated granular media

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The authors Lourenco *et al.* (2012) deserve to be congratulated on their ability to photograph the water menisci in unsaturated granular media. The authors also describe high values of the wetting contact angles ε for sandy loam (68.9°), clayey soil (65.2°) and quartz (30°).

The abstract of the paper under discussion, however, is misleading when it states that the paper shows ‘for the first time that, for a given water content, the contact angle between the air/water interfaces and grains can give a rise to a variety of meniscus shapes, with curvatures not all concave on the side of air’.

Sparks (1961, 1963a, 1963b, 1963c) addressed some similar problems 50 years ago. There exists a strong link between the influence of the values of $(u_A - u_W)$, the Bishop’s chi factor, and the behaviour of partly saturated soils.

In paper E.11 (Sparks, 1963b), Sparks introduced the stress equation for partly saturated soils as shown in equation (2) below

$$\text{Total stress} = \sigma_x = \sigma'_x + \alpha u_A + \beta u_W - \gamma T \quad (2)$$

where

σ_x = total stress in the x direction (with respect to atmospheric pressure)

σ'_x = effective stress normal to a section in the y – z plane

u_A = pressure in the air phase (with respect to atmospheric pressure)

u_W = pressure in the water phase (with respect to atmospheric pressure)

T = surface tension force in meniscus (force/unit length)

α, β = dimensionless parameters

γ = parameter with dimensions of length^{-1} because γ is calculated per unit area of section.

Equation (2) leads to the following equation (3) (see Sparks (1963b))

$$\text{Total stress} = \sigma_x = \sigma'_x - \chi(u_A - u_W) + u_A \quad (3)$$

where χ is the Bishop chi factor (Sparks used η), and

$$\chi = \beta + T\gamma/(u_A - u_W) \quad (4)$$

The value of β is equal to the proportion of the area on which water pressure acts, and hence its value lies between zero and unity. By definition, the value of β approaches unity as S_r increases to the saturated condition.

In a soil in which the grains are perfectly wetted (wetting angle, $\varepsilon = 0^\circ$), the value of $(u_A - u_W)$ may be expected to be large and positive if the soil is partly saturated. The value of $(u_A - u_W)$ will overshadow the other values in equation (4) and will approach zero only when the soil is fully saturated. Hence if $\varepsilon = 0^\circ$, the value of χ in equation (4) will normally be approximately equal to β , and hence χ does not exceed unity. However, in a soil in which the wetting angle ε is large, the value of $(u_A - u_W)$ can reach zero and can even become negative before the soil voids are filled with water.

Sparks (1963a: clause 2.4) stated that ‘The larger the

wetting angle ε , the greater is the possibility that u_W can be greater than u_A even when the water is in a pendular condition (i.e. before the pore water has become continuous’. The photographs in the paper under discussion seem to confirm this.

When wetting a soil that has a large wetting angle ε , it follows from equation (4) that the value of χ can exceed unity because $(u_A - u_W)$ is small, even though the pores are not yet full of water. A sensitive tension balance was constructed by Sparks, together with a student (C. van Tonder), the values of χ at different degrees of saturation were measured for two different soils (Sparks, 1963c: fig. iv, p. 90) (see Fig. 7).

It will be noticed that even in the case of the quartz the value of χ exceeded unity. In fact χ was measured to have a value of 1.73. The wetting angle quoted by Lourenco *et al.* (2012) for quartz is 30° , which is large enough to cause a value of χ greater than unity. Talc is not easily wetted by water and hence the value of χ equal to 1.45 occurred at a degree of saturation of only 82%. If the value of χ exceeds unity, then according to equation (4) this is only possible if $(u_A - u_W)$ is small and positive.

Eight factors which influence the value of χ were listed by Sparks (1963c: p. 99). The value of $(u_A - u_W)$ was a dominant parameter.

In a test using granulated talc, Sparks & van Tonder (Sparks, 1963c: p. 200) noted that ‘a sample of granulated talc was slowly wetted from below so that it remained unsaturated near its surface. The upper surface of the talc showed a visible upward movement when u_W exceeded u_A .’ This meant that if S_r is just less than unity in an unwettable soil, and if $(u_A - u_W)$ is negative, then the effective stress σ'_x can be nearly negative in equation (3) if the total stress is zero. In other words the chi factor in equation (4) can show a tendency to being zero or theoretically negative at this high value of S_r where $(u_A - u_W)$ is negative (see Fig. 8). This is also feasible as shown by the structure of equation (4) above. This proves that there is a discontinuity in the curve of chi plotted against S_r when u_A is equal to

Fig. 7. Measured values by Sparks & van Tonder (Sparks, 1963c)

Fig. 8. Curve for unwettable soil in tension rupture test (originally published in Sparks (1963b))

u_W . In an unwettable soil the chi value can approach an asymptotic limit when u_A is equal to u_W . This was predicted by Sparks (1963a: fig. 7), see Fig. 8.

Sparks (1963c: p. 99) suggested that the following nomenclature should be used for the Bishop chi factor: use χ (chi) for shear tests, ψ (psi) for consolidation tests and η (eta) for tensile rupture tests.

The discussor has never accepted that chi can vary only between zero and unity. He also believes that $(u_A - u_W)$ can be positive or negative and affects the value of chi.

The observations by Lourenco *et al.* (2012) confirm that the menisci geometries in real soils can be most complicated, and also that separate non-wetting droplets can appear in unexplained situations. Their work opens a new window, and further research is needed. The behaviour of the factor chi will also become part of such research.

Authors' reply

The authors thank Dr Sparks for his interest in the paper and acknowledge his research conducted in the 1960s. The authors wish to note that the contact angles Dr Sparks mentions (sandy loam 68.9°, clayey soil 65.2° and quartz 30°) have been published elsewhere (Letley *et al.*, 1962; Fisher & Lark, 1980). The contact angles in the paper (the spheres of Fig. 5) were estimated, as it is difficult to position the water–solid interfaces at right angles from the viewer to conduct the measurements.

The authors agree that the water menisci geometries can be quite varied. Contact angles greater than 0° are well known in the soil science literature (Doerr *et al.*, 2000). Their occurrence requires low soil water contents (Dekker & Ritsema, 2000) and the presence of organic carbon in the soil (Chenu *et al.*, 2000). Soil scientists mention a critical

water content at which soils change their wettability status (from wettable to water repellent and vice versa). Chenu *et al.* (2000) found that an increase in organic carbon content from 2% to 10% in clayey soils produced an increase in the contact angles from 20° to 60°. Other factors mentioned in the paper would equally play a role: direction and rate of water menisci movement (Taniguchi & Belfort, 2002) and the surface roughness characteristics of the particles (Bachmann & McHale, 2009).

The authors wish to add that wetting and drying was from water vapour (constant temperature of the Peltier stage and changing water vapour pressure) resulting in a uniform distribution of water menisci and a similarity of their shapes. Differently shaped menisci and a different wetting process (possibly with water menisci and bulk water) could be expected if liquid water is used instead.

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