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Soil structure dynamics — a journey to discovery

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Prologue

The path to discovery is seldom clear and never straight. Answers to long standing questions in one discipline may lie in neighboring scientific fields, hence ability to recognize, translate and adapt "foreign" concepts to the original problem make discovery such a rewarding endeavor (albeit frustrating at times). Here, I would like to share a journey to quantify soil structure dynamics via coalescence of aggregates or fragments formed by tillage induced by the action of wetting and drying cycles. The adapted models for representing these processes were derived from liquid phase sintering well known in material science using analogies with soil processes and parameters. Remarkably, it was a humble graduate student (Teamrat Ghezzehei) that transformed the physical modelling framework well beyond what I imagined possible. No one could have anticipated this is part of the journey, which reinforces the surprising and exciting path to discovery. Soil physics is at a cusp of a new era in understanding and representing soil structure for traditional arable lands and for natural landscapes (most terrestrial surfaces). The interactions among biophysical processes, land cover and climate give rise to feedbacks from which magically this illusive soil trait emerges and shapes soil ecological and hydrological functioning at all scales (root zones to continents).

Observations and a puzzle:

Early in my career at Utah State University I was investigating the effects of the so-called *surge flow* irrigation on water advance over soil surfaces. The method uses pulses of water at the head of the field that with less amount of water relative to continues application achieves more rapid advance (per amount of irrigation applied) and results in more uniform surface irrigation (Or and Silva, 1996). The key ingredient (well known for a while) was that with each wetting pulse and subsequent infiltration the friable surface consolidates a bit, and the infiltration capacity is reduced. Consequently, the next pulse of water travels over reduced permeability surface (with some entrapped air) enhances the advance per applied water amount. I became intrigued by the rapid and irreversible settlement and fusion of soil aggregates and quickly was able to deduce (the obvious) ramifications for the soil structure modification of tilled soils and seedbed with application of water. In other words, it became apparent that it is not the passage of time that changes the seedbed and require tillage again next season, but the action of water in "melting" or softening the soil combined by capillary forces exerted on these weaker aggregates that fuse or coalesce them into less microporous and more mechanically and structurally coherent soil surface. But what are the physical laws that govern such coalesce?

Liquid phase sintering analogue:

Here begins the second part of the journey, looking at analogue processes in neighboring scientific fields (via the literature) to develop a modeling framework for soil coalescence. It was the theory of sintering of powder compacts (Scherer, 1977) that appears to offer a framework for representing soil aggregate fusion under wetting-drying cycles. When powders of metal or glass are heated close to their melting temperatures, they tend to fuse at their contacts while maintaining the original shape of the grains. In Or (1996) an analogy was proposed composed of the following ingredients: (1) The softening of soil aggregates by wetting is analogous to the effect of high temperature on particles in sintering; (2) the welding of individual particles and reduction in pore space and surface area in sintering is analogous to the coalescence of individual aggregates at their contacts; (3) the coalescence process is spontaneous and driven by similar forces as sintering: surface tension, capillarity, and overburden load (Frenkel,1945; Heady and Cahn, 1970; Scherer, 1986). Application of the theory to the model of Scherer (1984) yielded prediction of changes in measured soil bulk density with wet soil viscosity as the only fitting parameter (values in the range of 1–20 MPa*s). We had to wait a few

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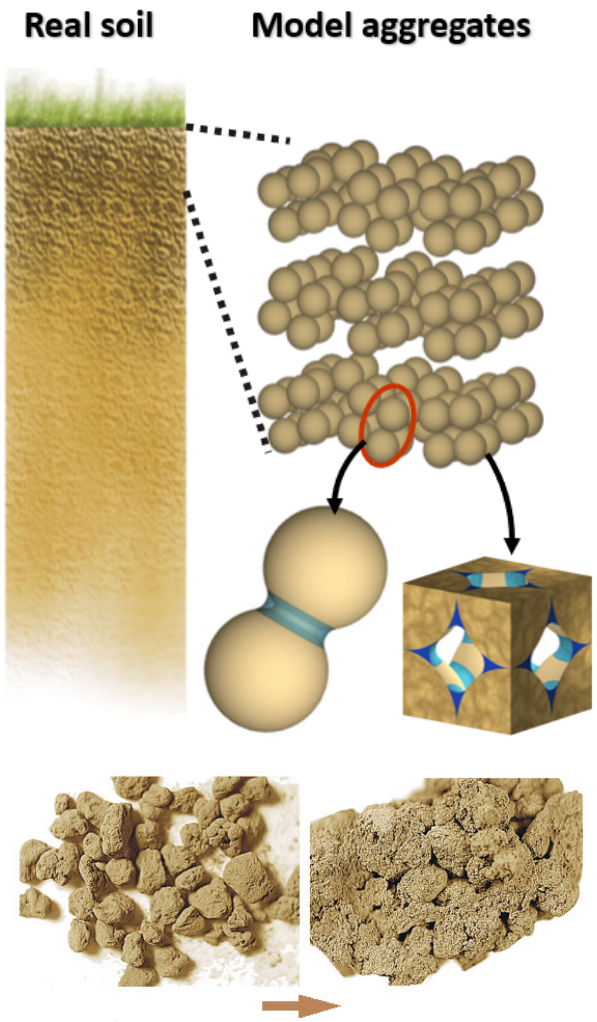


Fig. 1 (a) Conceptual model for aggregate coalescence under wetting and drying cycles considering a hierarchy of scales and simplified unit cells as model building blocks (an image of separated and coalesced Millville silt loam aggregates is shown) (Ghezzehei and Or, 2000; Or and Ghezzehei, 2001; Ghezzehei and Or, 2003).

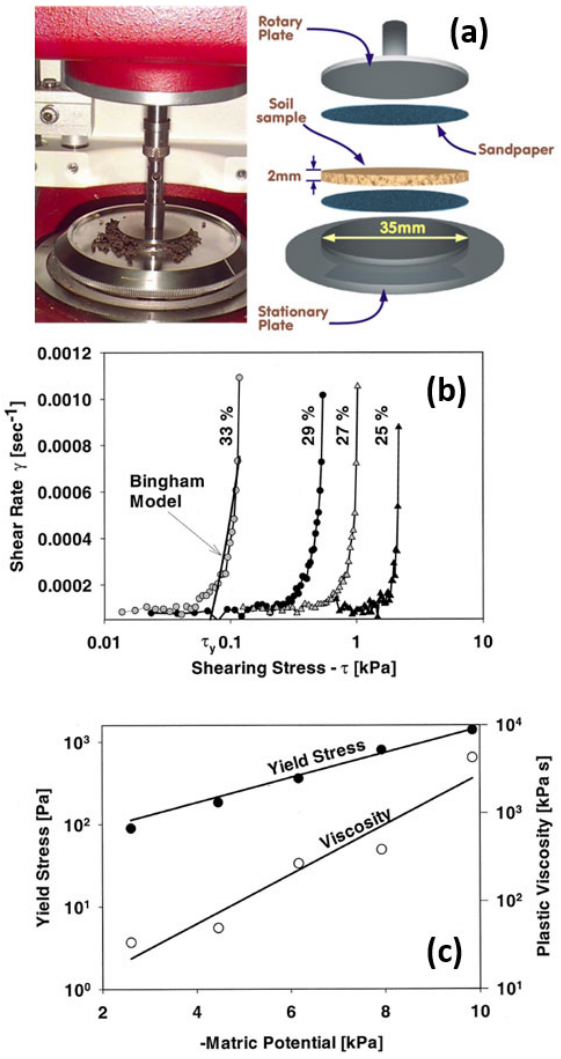


Fig. 2 (a) Parallel plate rotational rheometer (HAAKE RS75) used for measurement of soil rheological properties (b) measurements of Millville silt-loam strain rate vs shearing stress for different gravimetric water contents (c) derived coefficients of plastic viscosity and yield stress as functions of soil matric potential; for Millville silt loam soil (Ghezzehei and Or, 2001).

years to confirm these ridiculously high values of viscosity.

A model for wetting-drying effects on soil structure:

The theory had to wait a few years for a bright young student from Eritrea that joined our group. Teamrat Ghezzehei brought new skills and insights that enabled him to quickly assemble the pieces together and transformed the framework via new sets of differential equations that link aggregate size, soil type and water content (or matric potential) into a coherent energy-based framework (Ghezzehei and Or, 2001, see Fig. 1). Only one critical piece remained missing in this story, the direct measurement of soil rheological properties necessary for parameterizing the model (and explaining the speculative soil viscosity results of Or, 1996). Here again, Teamrat has shown his capabilities and foresight by reaching out to the Food Science Engineering at USU for using their Haake rotational rheometer to measure soil viscosity and yield stress under different water contents. Needless to say, that they were not overly excited to have their rheometer (used primarily for mayonnaise or chocolate paste characterization) be dirtied with field soil. We had to make many assurances and provide various services to gain access to the rheometer and determine the rheological properties of soils for a range of soil water contents (see example, Fig. 2). With the theoretical framework in place and soil rheological parameters available (BTW these nicely confirmed the speculative postulates made in Or, 1996) we were able to complete the cycle and offer physically-based predictions for soil structural changes following tillage (Ghezzehei and Or, 2000; Or

and Ghezzehei, 2001 and follow up studies). The unique aspect of the modeling framework was a departure from the static and macroscopic depiction of soil structure change offered by standard and static Geomechanical engineering theories. Simply because they focus of predicting stable foundations and roads and not dynamically evolving soil structure we seek to describe.

Aggregates to fragments and mature understanding of soil structure:

Over the years we were able to inject additional quantitative tools into modeling soil structure evolution including recent work on the mechanics of bioturbation by earthworms and growing plant roots (Ruiz et al., 2021) as well as how soil structure affects infiltration runoff at basin and global scales (Bonetti et al., 2021; Fatichi et al., 2020). More recently, we have proposed a framework for differentiating natural and managed soil structure that finally made a distinction between tillage induced soil fragments and naturally forming soil aggregates (Or et al., 2021). These are but a few drops in the ocean of unknowns that we must cross to better quantify this important and fragile soil trait.

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