EGU24-8571, updated on 24 Jan 2025
https://doi.org/10.5194/egusphere-egu24-8571
EGU General Assembly 2024

Unravelling succolarity to quantify multiscale petrophysical properties beyond porosity

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Characterising the complexity of spatial patterns and their underlying physics using a nonlinear approach is growing in many fields. Many features in geomaterials, such as pore and fracture systems, exhibit scaling behaviour, allowing their properties to be characterised using fractal theory.

The widely used fractal dimension is a ratio that compares how the level of detail in a structure varies with its size, measuring its space-filling ability. Lacunarity, derived from the Latin word "lacuna," meaning "gap," quantifies the “voidness” of a texture. Nevertheless, neither fractal dimension nor lacunarity can characterise the percolating properties of a fractal. Mandelbrot coined the concept of succolarity. Given that "percolare" in Latin translates to "to flow through," the term "succolare" (sub-colare) aptly conveys the concept of "to nearly flow through" in neo-Latin. A succolating fractal is characterised by almost containing the connecting paths that permit percolation, i.e., one below the percolation threshold. However, it remains a less known notion than the other two fractal counterparts. In the last ten years, succolarity has evolved from an idea to a computable parameter. It has characterised many patterns in different scales and fields, such as medical objects, material surfaces, and networks from nano-micropores to rivers.

In this contribution, we aim (i) to understand the physical meaning of succolarity and how it relates to pore networks and other petrophysical properties across different scales, and (ii) to provide new approaches to succolarity calculation. We implemented the succolarity algorithm using the gliding box-counting method. We then re-examined the published datasets for validation and comparison. The succolarity for 2/3D images of rock samples and synthetic models with various porous structures was also calculated for deeper understanding. Finally, we correlated the succolarity results with porosity, permeability, and other petrophysical parameters.

Our findings reveal that (i) succolarity contains information about a structure's anisotropy, phase fraction (e.g., porosity in the case of pore space), and percolation information. (ii) It is susceptible to connectedness. As we cut out smaller pores of a structure, succolarity decreases linearly until a pore size (porosity) threshold is reached; it drops significantly and follows a power law. (iii) Succolarity (Su) and permeability are fitted to an exponential relation: $k = ae^{bSu}$. The computation of succolarity excludes isolated pores for a given flooding direction, allowing it to reflect the flow properties better than porosity alone. (iv) Moreover, it is worth noting that using pressure or velocity field in the succolarity calculation algorithm would endow it with a clearer physical meaning than being a proxy for porosity.