Porosity Reviewed: Quantitative Multi-Disciplinary Understanding, Recent Advances and Applications in Vadose Zone Hydrology

Matthys A. Dippenaar
Engineering Geology and Hydrogeology, Department of Geology, University of Pretoria, Private Bag X20, Hatfield, 0028, Pretoria, South Africa
+27 (0)12 420 3117
madip@up.ac.za / madippenaar@gmail.com / www.up.ac.za/geology

Abstract: Porosity – one of the most basic mechanical properties of a medium – has implications in a vast range of disciplines and used for a similar vast range of applications. These include, for instance, the storage and flow of water; the compressible component of earth materials, which can be subjected to consolidation under loading; the variable parameter in the swelling and shrinkage of clays; and possibly a governing parameter in the formation of wetlands and perched water tables. This review notes the relevance of a four-fold quantification of porosity for vadose zone studies, viz. (1) type (matrix or structure), (2) scale (submicro to macro scale), (3) connectivity, and (4) water saturation. This is followed by a review of recent advances in the quantification and description of porosity in porous media (visual and remote sensing methods, porosimetry, geometrical approaches, empirical estimations, densest packing simulations, etc.), the applications to quantification of hydrological parameters, and a brief glimpse into the significance of porosity in a temporary hillslope wetland underlain by Archaean Lanseria gneiss in South Africa. Final comments are made regarding areas where quantification of porosity is problematic.

Keywords: porosity; void ratio; vadose zone; effective porosity; fractal; microstructure; porosimetry; ferricrete; temporary hillslope wetland

1. Introduction

Albeit a straightforward concept (how hard can determining the ratio of voids to solids possibly be?), quantification of porosity is often significantly simplified. The importance of porosity in hydrology as a primary input parameter in almost all subsequent calculations is overlooked and the parameter is estimated without any validation, resulting in significant unquantifiable errors in hydraulic parameters. However, the simple percentage value of porosity is only one such aspect. The importance of type, scale and connectivity of porosity is commonly understood, but rarely evaluated in significant detail.

A detailed discussion in Miller and Gray (2002) on the status of groundwater research accentuates a number of aspects requiring more research and where our understanding is often not sufficient. Reference is made particularly to preferential flow paths such as fractures and the resulting complicated accounting of interactions between these fractures and the flow through the primary pore space. They continue to elaborate on the difficulty of accounting for scale ranging from molecular to regional field problems. Fractured systems are singled out due to the difficulty in characterising and modelling fractures with available methods and because of their interaction with the porous matrix.

As this is a review paper, basic concepts will be described concisely for the sake of cross-disciplinary agreement. It is impossible to cover the whole range of methods applicable to porosity. The purpose of this paper is primarily to summarise considerations in the quantification of porosity, to review recent advances in the quantification of porosity, to apply selected inexpensive and readily available methods, and to summarise significant gaps in the understanding of porous systems with respect to their hydraulic behaviour.

The importance of porosity spreads over a wide range of disciplines. For the hydrologist or hydrogeologist, the porosity determines the void space available for water storage, as well as the capillary rise and ability of the void space for fluid flow, which depend on the size and continuity of the pore spaces. For the engineers, geologists and soil scientists, additional emphasis is placed on consolidation, shrinkage and swelling behaviour, surface subsidence and variation in material properties due to leaching and precipitation processes. All of these are important, making it necessary to consider the widest possible definition of porous media; i.e. to include all types and scales of porosity, as well as all degrees of connectivity, as opposed to only connected matrix porosity.

2. Porosity Explained

In any natural system, three inorganic phases can coexist: solids (S), and fluids in void space (V) commonly comprising water (W) and air (A) as shown in Fig. 1. Common denotation of these three phases is either by mass (M) or by volume (V) with the subscripts as noted above defining what the mass or volume relates to in terms of the total (T). This is also the most basic definition of porosity as a simple ratio of the volume voids to the total volume of sampled material as per Eq. 1. Numerous different symbols are used for porosity, including Greek eta (η as used in this paper), Latin n and Greek phi (Φ).

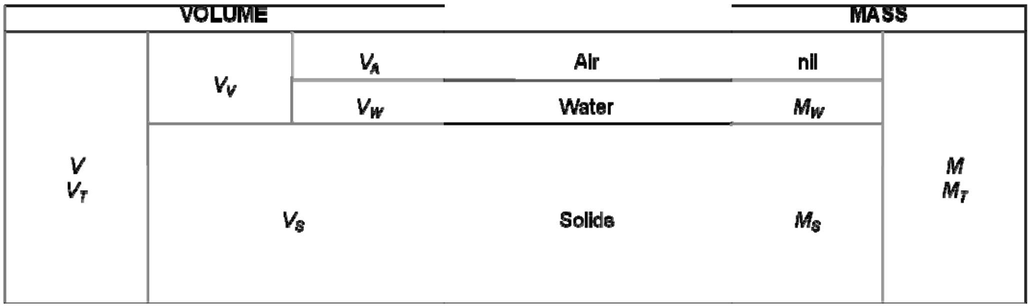

Figure 1. Phase relationships for the definition of porosity and void ratio (e.g. Craig 1999; Knappett and Craig 2012).

$$\eta = \frac{V_V}{V_T} \qquad \text{Eq. 1}$$

In order to address changing porosity with changes in material density for engineering purposes, geotechnical engineers often use the void ratio e. This parameter ratios the volume of voids to the volume of solids and relates to the porosity as shown in Eq. 2.

$$e = \frac{V_V}{V_S} = \frac{\eta}{1-\eta} \qquad \text{Eq. 2}$$

Unless undergoing volume change, the pore space or void space remains the same regardless of whether water or air occupies it. Additionally, the solid phase creates the void space, but in hydrology this void space becomes the vital parameter in quantifying and understanding fluid storage and movement through porous media. It is, therefore, important to understand the void space geometry before considering the solids and fluids comprising the medium.

Classification of porosity can be based on a number of aspects. Essentially, three important aspects should be considered when addressing porosity:

- Type of porosity, i.e. primary (textural, soil material, matrix) porosity versus secondary (structural, soil mass, fracture) porosity to account for the differences in the nature of the void spaces and connectivity
- Scale of porosity, i.e. submicroscale, microscale, mesoscale and macroscale porosity to account for variations in porosity with varying scales of consideration (the REV concept)
- Connectivity of porosity, i.e. whether it allows the transmission of water as opposed to porosity which cannot contribute to the flow of water (dead-end or non-connected pores).

Although these considerations are the personal view of the author, the inclusion of one or more of these considerations appear throughout academic research. Each of these will be addressed separately to clarify the context and to emphasise the importance of consideration of all three together.

2.1. Type of porosity

When distinguishing between rock and soil in terms of hydrology, the main importance is probably the significant differences between texture and structure that may influence the movement of fluids through the medium. Soil represents that interface between the atmosphere and lithosphere, interacts with the hydrosphere and sustains growth in the biosphere and can be distinguished from inert rock by the presence of organisms, a structural organisation due to pedogenic processes and a capacity to respond to changes in the environment (White 1997). However, soil can be defined in one discipline to include certain materials, which in others are considered rock due to the application of the classification (as evaluated in numerous cross-disciplinary papers and as summarised in for instance Dippenaar 2012). However, when considering the concept of porosity, which is clearly defined mathematically, nomenclature becomes irrelevant and the distinction between types of porosity is based on the morphology of the pore spaces resulting from the formation of said pore spaces. This pore space geometry is subsequently subdivided into two (and occasionally three) distinct classes:

1. Primary porosity, also termed textural, matrix or interstitial porosity in science and porosity relating to soil or rock material in engineering, refer to the void space formed simultaneously with the formation of the soil or rock. This can, therefore, be viewed as the openings between distinct soil grains or minerals forming a rock.
2. Secondary porosity, also termed structural porosity in science and porosity relating to soil or rock mass in engineering, refer to the void space formed after formation of the soil or rock. This is more noteworthy in rock as fractures (resulting from, for instance, jointing and faulting) or metamorphic textures (such as gneissosity), and to a lesser extent in soils as preferential paths due to, for instance, plant roots, insect or worm burrows, prismatic jointing and dessication cracking.
3. Tertiary porosity is often considered together with secondary porosity and relate almost exclusively to soluble rock. In hydrogeology, karst is the prime example of this where primary and secondary porosity are altered by extensive chemical weathering processes such as dissolution to create large void space as is commonly represented by dolomite cavities.

Primary porosity is the easiest to quantify as fairly homogeneous soils in a naturally consolidated packing will result in porosity being a function of the effective grain size (d_e) and the packing of the uniform spherical grains of diameter d_e. With increasing textural variability, the empirical estimation of primary porosity becomes increasingly inaccurate. Applying the effective grain size diameter to tetrahedral and cubic packings, standard pore relationships and porosities exist as shown in Fig. 2. Given this scenario, the porosity results in 0.260 (26.0%) for tetrahedral packing and 0.476 (47.6%) for cubic packing. Important to note is that the porosity is for materials composed of uniform sized spherical particles is not dependent on the effective grain size diameter, but solely on the packing of the grains. However, in non-uniform materials, finer grains are able to clog the void spaces formed and the porosity will be lowered substantially. This concept has been discussed in a vast amount of topical groundwater-related textbooks (e.g. Fetter 1994; Bear 2007; Todd and Mays 2005; Younger 2007).

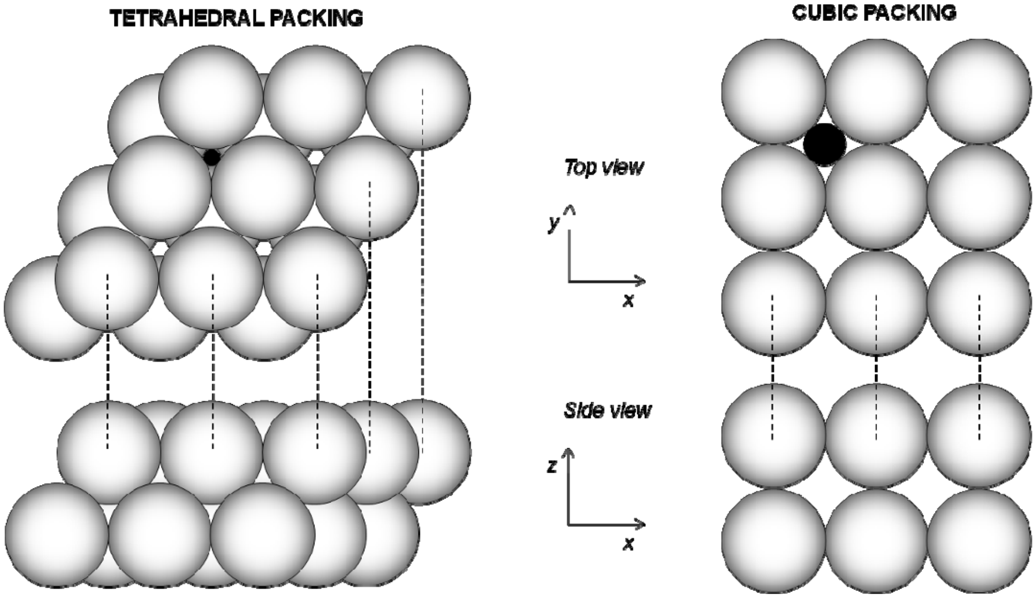

Figure 2. Typical packing of naturally consolidated uniform spherical grains of similar diameter; black grains indicate probable clogging of void spaces by smaller diameter particles which result in lower porosity.

Primary porosity is common in most unconsolidated sediments and unmetamorphosed sedimentary rocks such as sandstone. An example of Karoo Supergroup sandstone from the Kruger National Park (South Africa) is shown in thin section microscopy in Fig. 3, clearly showing the quartz grains and the open voids.

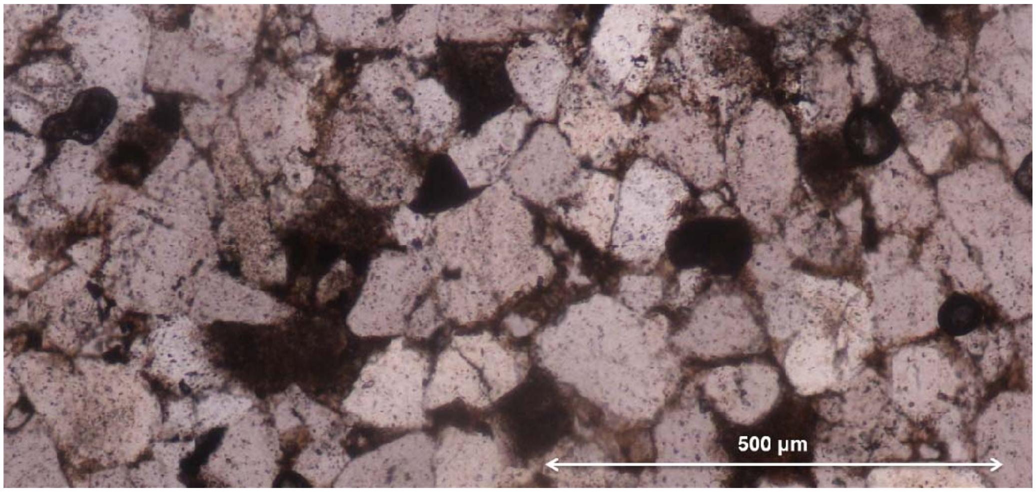

Figure 3. Primary porosity (dark patches) in Karoo Supergroup sandstone from the Lower Sabie region (Kruger National Park, South Africa); note the lack of connectivity between some of the void spaces.

Secondary porosity is more difficult to quantify, especially as a separate porosity has to be determined for primary porosity as well, and because each structure can have it's own properties. Zoomed in to a wide-open structure (the REV concept as will be discussed later), the structure may have a porosity of unity as it comprises only void space. In this instance, characterisation of other aspects become increasingly important, notably the continuity of the structure, its aperture and clogging or coating of the planes by for instance clay minerals and precipitates. An example of secondary porosity is shown in Fig. 4. in outcropping fractured Lanseria gneiss from Midrand to the north of Johannesburg (South Africa).

Figure 4. Secondary porosity in the form of parallel joints in fractured Lanseria Gneiss (Johannesburg Dome Granite) from Midrand (Gauteng Province, South Africa); note the varying apertures.

Regarding secondary porosity, a *fracture* can be defined in structural geological terms as any "… discontinuity across which there has been separation…", and including faults and joints. This can be elaborated to a fracture zone, referring to a zone of such fractured rock, notably with reference to aquifer materials (Keary 2001). The term fissure is often applied, especially in the United States of America, to replace fracture. According to the American Geological Institute (1976) a fissure is "… an extensive crack, break or fracture in the rocks" and usually excludes mere joints or cracks that persist only for short distances. As opposed to fractured or fissured rock, intact refers to unweathered and unfractured state and therefore the absence of secondary porosity.

Fractures include faults and joints and the further distinction between fractured rocks and fractured porous rocks become important. *Fractured rocks* relate to the fractures themselves, whereas *fracture porous rock*s include the contribution of the porous host rock. This distinction results in different porosity and permeability values and is characterised based on *single fracture models* or *fracture networks* (Berkowitz 2002). Potential problems with fracture models and, notably, the cubic law is discussed in great detail by Witherspoon et al. (1980) and include the difficulty of measuring exact facture aperture, the roughness of the fracture surfaces, the closing of portions of the fractures under stress and the influence of weathering

Pore radii and its influences on capillarity are a function of pore geometry. Three idealised geometries (cylinder, parallel plates and sphere) are shown in Fig. 5 together with the calculation of pore volume, surface area, and volume to surface ratio.

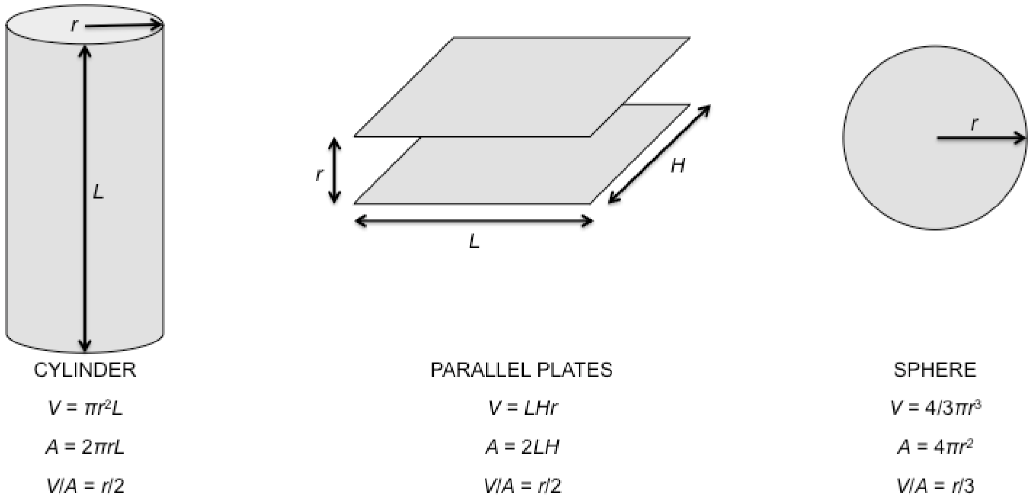

Figure 5. Idealised soil pore geometries (after Lu and Likos 2004).

2.2. Scale of porosity

The scale of porosity can best be visualised by the *representative elementary volume* (REV) concept described in detail by numerous authors (most notably in Bear 2007; Bear 1988). These so-called domains of microscopic and macroscopic heterogeneity refer to the different scales of porosity detected at varying scales of investigation with the domain of macroscopic heterogeneity possibly referring to, for instance, major structural features such as faults and shear zones (Fig. 6).

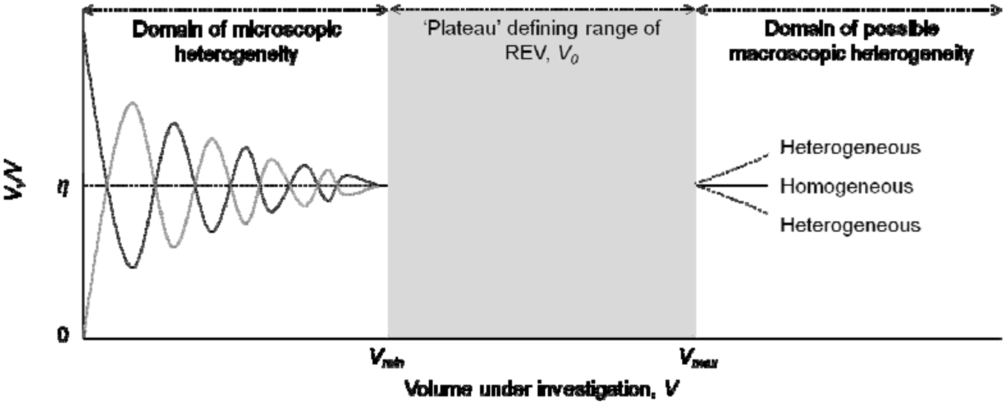

Figure 6. The representative elementary volume depicting zones of microscopic and macroscopic heterogeneity (after Bear 2007).

Another means of simplifying the concept is to visualise a fixed unit volume with fixed porosity with uniform distribution of the porosity. Fig. 7 shows a possible three-joint fractured system (two vertical, one horizontal) resulting a rock blocks of different size and voids with different apertures. Although the porosities of all three these systems may be similar, the noteworthy distinction is in the scales resulting in different pore sizes. From a purely sedimentological point-of-view this may not be extremely important, but the competing adhesivecohesive forces will vary significantly in these systems, resulting in the retention of certain moisture contents in the smaller pore spaces while resulting in gravitational flow in the larger ones. Additionally, the radius of the pore space is invertedly proportional to the height of capillary rise.

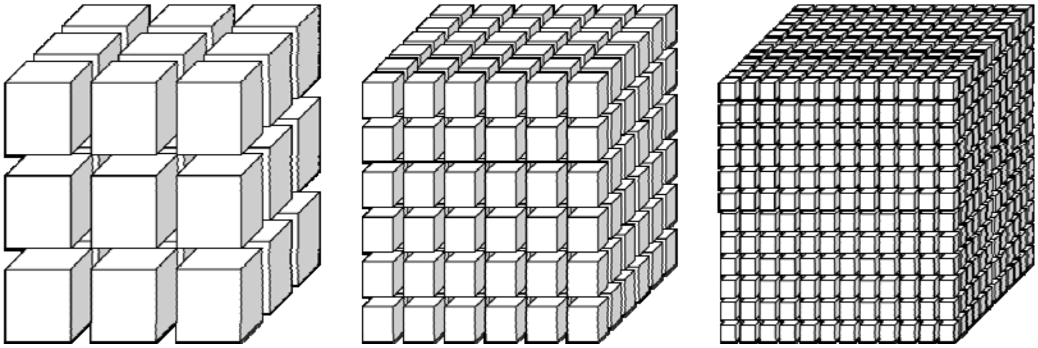

Figure 7. Similar porosity schematically depicted at varying scale in a fixed unit volume.

Multiple REVs can exist depending on the scale of investigation. It is, for instance, possible that a sample of 1 cm^3 can have a fixed porosity, which is valid for the volume of investigation, but that a completely different porosity prevails on a regional scale due to, for instance, a significant shear zone overriding the hydraulic properties of the smaller scales. Numerous authors (e.g. Dexter and Richard 2009; Dudoignon et al. 2007; Kutílek 2004) evaluated the various scales of porosity. In summary, for soils, *macropores* typically relate to vertical prism joints or any other pores which are non-capillary; *mesopores* are typically due to shrinkage cracking and 100 – 2 000 µm; *micropores* are due to the clay-matrix and particle arrangement and are capillary pores; and *submicropores* relate to water molecules and flow path inhibiting sized capillary openings. The pore sizes according to these texts roughly correlate as follows: macropores typically relate to coarser than gravel, mesopores fall within the sand and silt range, micropores are typically related to the clay fraction, and submicropores go into the water molecular size range.

Fig. 8 summarises typical influences of soil and rock texture and structure over four broadly defined scales of porosity. Although the boundaries are not as clearly defined, it is important to note that different scales of measurement will influence the REV, and the voids formed during formation of the material versus those formed at a later stage will influence the pore sizes and interconnectedness.

	Primary / Textural Porosity Soil Material	Secondary / Structural Porosity Soil Mass
Macroporosity	Non-capillary, e.g. Corestones, differential grading, columnar jointing and heterogeneity; gravel and coarser	Non-capillary, e.g. Fractures, joints, fissures, piping, dongas
Mesoporosity	Cusp of capillarity, e.g. Grading and variation; sand and silt	Cusp of capillarity, e.g Bedding, foliation, shrinkage cracks, termite nests, root voids
Microporosity	Soil aggregates and capillarity, e.g. Soil grading (notably clay) and effective pore size diameter	Structural capillary pores, e.g. Near-closed structures, laminations, leached zones
Submicroporosity	Effective clogging texture, e.g. Clay content, adsorption and diffusion of water; water molecules	Effective clogging structure, e.g. Joint infilling, precipitates

Figure 8. Summary of typical (although not as clearly definable) scales of porosity at the hand of relevant examples (adapted from Dippenaar et al. 2010).

Additional to the scale of porosity is the *homogeneity* and *isotropy* and the natural system. With vertical and spatial variation in earth materials (texture, consolidation, structural influences, pedogenetic processes, eluviation and illuviation, etc.) porosity will also change. Cognisance of this is required when addressing hydrology, as different porosities will indefinitely influence the hydrological behaviour of earth materials.

2.3. Connectivity of porosity

When considering porosity in hydrology, it can be subdivided into essentially two components, namely *effective* (drainable or interconnected) porosity and *non-effective* (non-drainable, disconnected or dead-end) porosity. The sum of these two are referred to as the volumetric porosity as determined in Eq. 1 and the non-drainable porosity should theoretically be excluded from hydrological assessments as it cannot contribute to the movement of water, although it is an important parameter in engineering, notably when quantifying consolidation. Effective porosity is sometimes estimated based on the specific yield, S_Y, referring to that “volume of water that will drain by gravity per unit drop in the water table per unit volume of aquifer” or the drainable porosity. The remaining water attached to the solid surfaces in the voids is referred to as the specific retention, S_R (Weight 2008) as shown in Eq. 3.

$$\eta_T = S_Y + S_R \qquad \text{Eq. 3}$$

Various terminologies exist when relating porosity respectively contributing to and not contributing to flow. The terms effective porosity (η_E as the dominant mode of fluid transport through flow), diffusion porosity (η_D as the dominant mode of aqueous diffusion) and residual porosity (η_R where not flow takes place due to lack of inter-pore connection) are described by Norton and Knapp (1977), whereas Tullborg and Larson (2006) employ connected porosity (η_C which are pores available for water saturation) and unconnected porosity (η_N = total porosity minus connected porosity). These parameters are placed in context in Eq. 4 (symbols and subscripts have been standardised from original texts).

$$\eta_T = \eta_E + \eta_D + \eta_R = \eta_C + \eta_N \qquad \text{Eq. 4}$$

Effective porosity is governed by the interconnectivity of voids, which result essentially from the pore space geometry due to the packing of the solid phase of the material. At the most basic level, this entails cubic versus tetrahedral packing as shown in Fig. 2. However, as soon as grain sizes and shapes are allowed to vary, preferential packing scenarios can occur due to, for instance:

- Interlocking grains, clay bridges between coarser particles and redistribution of fine materials due to percolating water in soils
- Effects of cementation and lithification in sedimentary rocks, crystallisation in igneous rocks and subsequent metamorphism.

Based on this heterogeneity and anisotropy, void spaces cannot merely be measured and assumed for the bulk of the sample and two additional aspects now become relevant: (1) the evaluation of the actual pore space geometry, and (2) the simplification of the pore space geometry to a simpler, more useable parameter.

In terms of the actual pore space geometry, one can distinguish between *pores* and *throats* with pores being the larger void spaces and throats the narrower connecting void spaces. A *pore section diameter* can then be determined as the diameter of a circle or ellipse with an area equal to that of the cross-section of the pore. To help with the calculation of this pore space geometry, the *feret* concept can be used where a feret represents the spacing between two parallel tangents to a void feature in a given direction. The maximum feret refers to the maximum possible distance between two such lines and the minimum feret to the minimum distance or to that distance perpendicular to the maximum feret (Mathews et al. 1997). Entrance of water into the pore therefore depends on the size of the pore throat and the storage of water on the size of the pore itself – an important aspect, which also governs the processes of drainage and imbibition. Fig. 9 illustrates pores and throats, the ferret concept and the presence of unconnected pores.

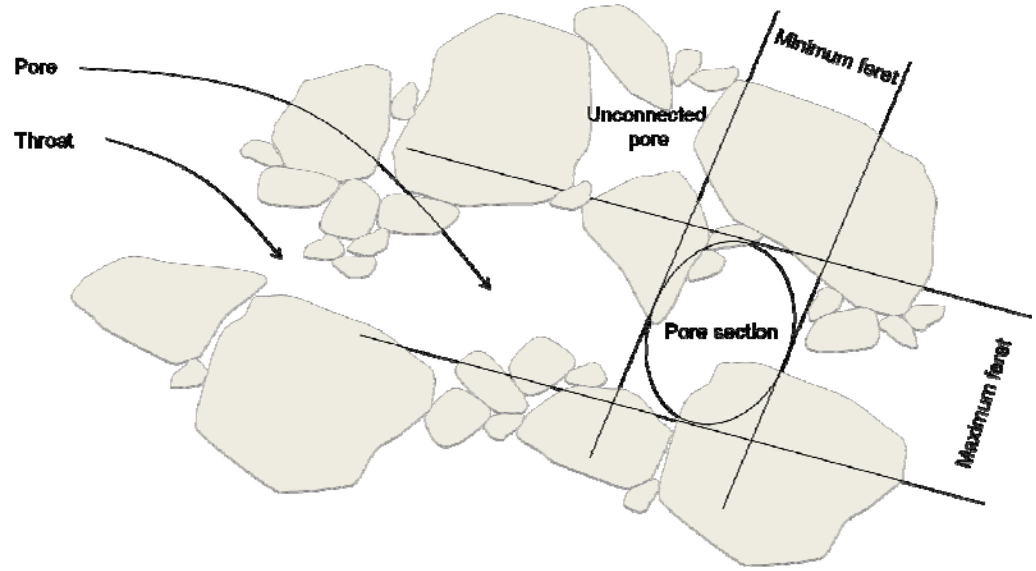

Figure 9. Pores, throats, ferrets and unconnected pores (adapted from Mathews et al. 2007).

The connectivity of pore spaces also governs the movement of ions and fines (clay minerals) with moving water. These ions can mobilise and precipitate and the clay minerals can clog the soil skeleton depending on the ability of water to move through the material. The result of these processes is very distinct vertical and spatial variation in soil hydraulic properties, as certain portions of the profile will become more porous whereas a subsequent horizon may become clogged. Fig. 10 shows typical *clay-related clogging microstructures* in context of the vertical distribution of water in the crust. The vertical leaching of clay minerals – notably kaolinite in coarse-grained soils – typically result in a kaolinite-rich horizon overlain by a leached collapsible horizon, both with distinctly varying porosity. Aggregate formation results in increased strength and changes in soil structure, which – as a direct function of porosity – will inevitable influence hydraulic behaviour (e.g. Horn et al. 1994; Skolasinska 2006).

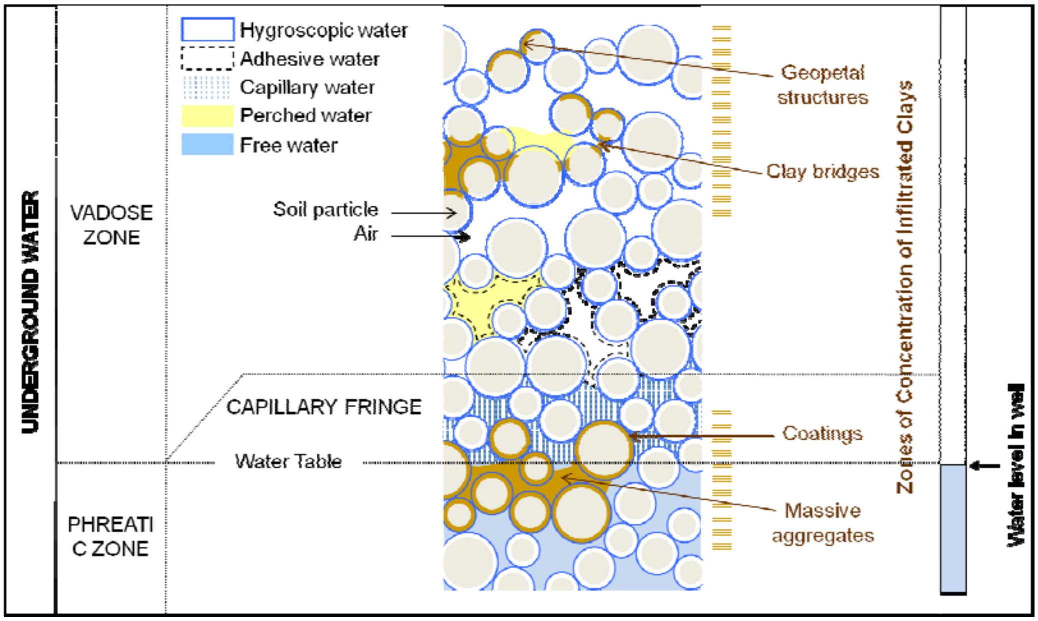

Figure 10. Vertical distribution of water in the crust and the concomitant clogging structures (adapted from Shaw 1994; Skolasinska 2006; Moraes & De Ros 1990).

Changes in hydrological behaviour can also result in perched or fluctuating water levels, which in turn may result in the development of pedogenic soil horizons. *Pedogenesis* is influenced by the subsurface, down-slope drainage of water until a point on the slope is reached where precipitation of transported ions commences. Based on the climatic conditions and the available ions mobilised, these pedocretes include, for instance, ferricrete (Fe-enriched), laterite (generally aluminous) and calcrete (Ca-enriched). Of importance here is that the pedocrete is formed from either gravitational or rising water and therefore alters the porosity vertically downwards or upwards as pedogenetic or groundwater pedocretes respectively and the direction of formation is evident by increasing mottling (Fig. 11; McFarlane 1976). The resulting pedocrete can then range from highly porous to very low porosity depending on the stage of formation. Alternative terminologies and theories on the development of these cemented soils (e.g. duripans, duricrusts, plinthites) are discussed in numerous topical references (e.g. Blatt and Tracy 1997; Brady and Weil 1999), but pedocretes almost always refer to cemented materials, whereas the pans in soil sciences often involve compacted materials which do not necessarily exhibit any cementation, or alternatively entail cementation by means of clay minerals.

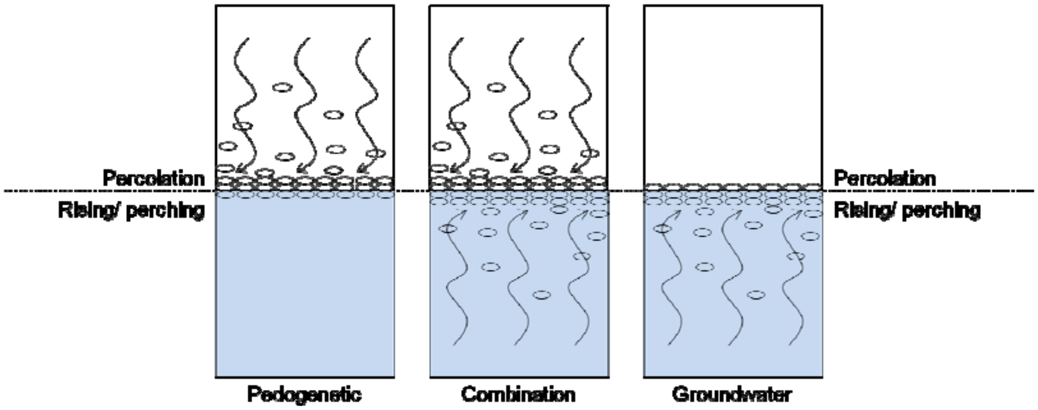

Figure 11. Pedogenetic (forming from percolating water) and groundwater (forming from rising water) pedocretes and the characteristic increasing mottling in the direction of formation (adapted from McFarlane 1976).

2.4. Type, scale and connectivity combined

Each in its own capacity appears easily identifiable, notably form visual observation of specimens at different scales. Nonetheless, the quantification of each in order to accurately determine hydraulic conductivity, for instance, is required for proper hydrological understanding. Porosity in hydrology and, more specifically, vadose zone hydrology and hydrogeology, is not merely a volume relationship. The type, scale and connectivity need to be addressed quantitively in detail.

3. Porosity in Hydrology

Although significant overlap exists in the consideration of type, scale and connectivity of porosity in hydrological terms, the inclusion of specific attributes to the three considerations are based on the influences of the attribute to the hydrological behaviour of the material. In more practical terms, type of porosity relates to what needs to be investigated (texture or structure) and to how a hydrogeologist would classify it was it an aquifer. Similarly, scale of porosity addresses adhesion and cohesion and subsequently influences important concepts such as soil suction, capillarity and field capacity. The connectivity is determined directly from the type and scale of porosity, but pertains exclusively to the ability of the medium to allow water entry to a pore, to store the water in said pore and to transmit water between pores.

Movement of water is governed by a number of forces, notably gravity for acceleration (also influenced to a lesser degree by overburden pressures and degassing) and adhesion, turbulence and friction for retardation (Kovács 1981). The presence of connected pores will undoubtedly act to promote the movement of water, provided that the pore spaces are vacant for the entry of water and that the porosity does not significantly decrease in the direction of flow. However, the counteracting forces are all also directly dependent on the porosity. Whether adhesion will retain water to the mineral surfaces or whether cohesion will result in pore water available for drainage is a relationship between the surface area of the pore and the available water in the pore space. As the moisture content increases, more of the pore space becomes occupied with water, resulting in increased unsaturated hydraulic conductivity until a theoretical maximum saturated hydraulic conductivity is encountered at saturation (e.g. Fitts 2002). This basic yet fundamental relationship is shown in Eq. 5 where the volumetric moisture content θ is the volume water divided by the total volume, Eq. 6 where the water saturation S_W is volume water over volume voids, and Eq. 7 where, at saturation, $S_W = 1$ resulting in $\theta = \eta$ and the hydraulic conductivity K equal to the theoretical maximum saturated value K_{sat}.

$$\theta = \frac{V_W}{V_T} \qquad \text{Eq. 5}$$

$$S_W = \frac{V_W}{V_V} \qquad \text{Eq. 6}$$

$$\begin{aligned} &S_W = 1 \\ &\quad \Rightarrow \theta = \eta \\ &\quad \Rightarrow K = K_{sat} \end{aligned} \qquad \text{Eq. 7}$$

In hydrology, this therefore adds a fourth consideration to the concept of porosity, *viz. water saturation of the pore space*, as changes in the moisture content or the degree of saturation will result in different hydrological behaviour of the same porous material. The evaluation of the three porosity considerations and the fourth consideration relating to water saturation of the pores combined will increase confidence in vadose zone hydrological assessments (Fig. 12).

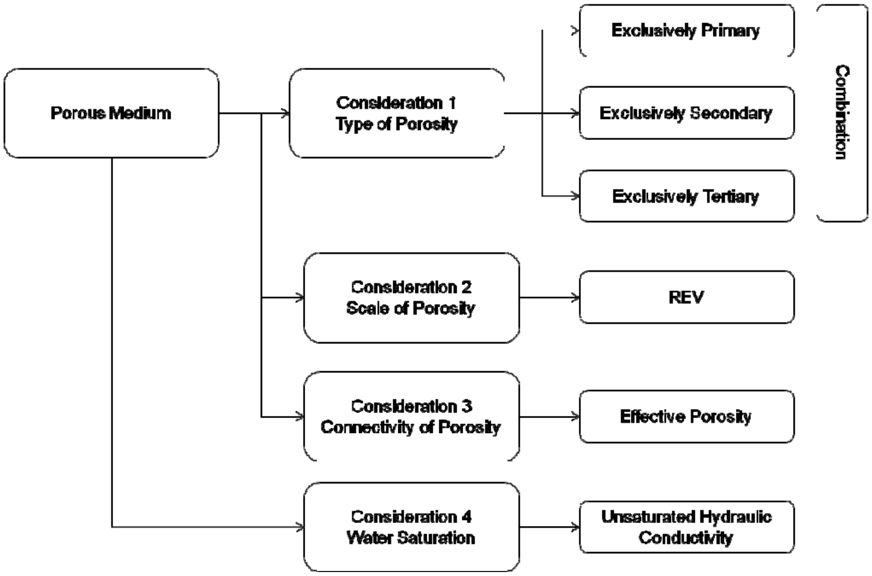

Figure 12. Evaluation of porosity in a porous medium for application in vadose zone hydrological studies.

4. Quantification of Porosity

4.1. *Basic relationships to quantify porosity*

Porosity is often estimated based on the uniformity coefficient according to Istomina (1957), as discussed in Van Schalkwyk and Vermaak 2000). The uniformity coefficient C_U relates the particle size diameter that 60% of the material is finer than, to that diameter where 10% of material is finer (Eq. 8). This is, however, only applicable to soils with fairly uniform fractions and cannot be applied when clay is present in the soil.

$$\eta = 0.255 \cdot \left(1 + 0.83^{C_U}\right) \qquad \text{Eq. 8}$$

$$C_U = \frac{d_{60}}{d_{10}}$$

A more common laboratory method relates the saturated density ($V_V = V_W$) to the oven-dried density ($V_V = V_A$) as shown in Eq. 9. The saturated density ρ_{sat} minus the dry density ρ_D can be converted to the moisture content (Eq. 5), which is equal to the available porosity at saturation (Eq. 7).

$$\rho_{sat} = \frac{M_S + M_W}{V_T} \qquad \text{Eq. 9}$$

$$\rho_D = \frac{M_S}{V_T}$$

$$\frac{\rho_{sat} - \rho_D}{\rho_W} = \frac{V_W}{V_T} = \theta_{sat} = \eta$$

Another effective method of determining porosity is through quantitative mineralogical composition as supplied through X-Ray Diffraction (XRD) and X-Ray Fluorescence Spectroscopy (XRF). Fractions (f_M) of minerals are obtained, the sum totalling one. Densities of these individual minerals (ρ_M) are readily available in published literature (e.g. Deer et al. 1996). These results can be used to determine an average solid phase density (ρ_S) that relates to the bulk dry density of the sample (ρ_D) as shown in Eq. 10. The benefit of this method is its incorporation of the distribution of minerals with varying density, and not only the textural changes from particle size distribution.

$$\eta = 1 - \frac{\rho_D}{\rho_S} = 1 - \frac{\rho_D}{\sum f_M \cdot \rho_M} \qquad \text{Eq. 10}$$

4.2. *Advances in quantification of porosity*

A number of authors has considered alternative means or have reviewed existing approaches to the accurate quantification of porosity during the last two decades. Too numerous to supply in this paper, selected approaches to the conceptual understanding of porosity quantification are briefly detailed below.

4.2.1. Density relationships

A study evaluated the porosity of drill core by comparing bulk dry and grain densities. Two of the key findings were that connected porosity are aligned parallel to foliation and that laboratory porosities are generally higher than in situ because of factors such as stress release during sampling (Tulborg and Larson 2006).

4.2.2. Empirical relationships

Effective porosity is roughly equal to the total porosity minus the volumetric water content at field capacity, or alternatively at –33 kPa of suction to – 66 kPa of suction for very clayey soils. This was evaluated for paddy soils and used to estimate saturated hydraulic conductivity according to the Kozeny-Carman equation (e.g. Aimrun 2004). Flint and Selker (2003) considered the porosity function applied in numerous empirical hydraulic conductivity estimates in Nevada, concluding that K ranges over two to four orders of magnitude when using these empirical relationships.

4.2.3. Visual, remotely sensed and porosimetry methods

The historical developments in soil micromorphological imaging are discussed in detail by Mermut (2009), noting a number of problems, including the need to evaluate shape, size, distribution and nature of soil particles and pores.

Pore geometry and porosity were investigated through thin section analyses to evaluate the influences thereof on initial water saturation, finding that an increase in smaller pores result in higher initial water saturations (Coskun and Wardlaw 1995). Virgin et al. (1996) considered the relationship between two-dimensional and three-dimensional porosities to address the randomness of microstructure in order to address macroscopic physical properties. Applications pertaining to geographic information systems (GIS) have also been used to compile schematic maps of soil pore spaces with the benefits of seeing distinct grains, distinguishing sizes and shapes of pore spaces, pedofeatures and plant residues (Skvortsova et al. 2006).

A fuzzy random model of soil pore structure was evaluated through converting the medium to a set of pixels with a value of zero for solids and unity for pore spaces. Pixel swapping was employed to generate structures and further work towards a three-dimensional approach has been stated as on going (Moran and McBratney 1997).

Microstructure techniques and their importance in unsaturated investigations relating to engineering are discussed in a review by Romero and Simms (2008).

They specifically evaluate mercury intrusion porosimetry (MIP) and environmental scanning electron microscopy (ESEM). Similar porosimetry techniques are also discussed by, for instance, Miguel and Bonder (2012). The parameters relating to porosity evaluated via these methods include dominant pore sizes, pore size distribution (PSD), soil microstructure and predictions if volume changes. This review also supplies an summary of microstructural methods and the physical properties at microstructural scale as well as the macroscopic behaviour.

Geostatistical analyses of borehole image data and the use of borehole resistivity imagery have been used with success to visualise porosity in heterogeneous borehole core (Tilke et al. 2006). One of their main findings was that other standard logging methods might smooth out heterogeneity.

Shougrakpan et al. (2010) evaluated soil macroporosity in different land uses and land covers in northeastern India based on dye patterns analyses. They conclude that such analyses can be beneficial in groundwater contamination assessments due to preferential leaching and infiltration.

4.2.4. Random and densest packing simulations

True porosity is defined as the porosity of randomly packed material in a container without influence by the container's walls and is related to density and is inversely proportional to the representative size of the container into which particles are deposited. A simulation of random packing of equal spheres in a finite cubic box followed by simulations adjusting the floor of the box resulted in good findings with an assessment of the influence of the walls and floor on the estimates (Krukama et al. 2000).

Straughan (2010) considered the dependence of the Darcy and Forschheimer coefficients on porosity in a porous material comprised of spherical beads. These are both, however, based on disturbed materials composed of uniform spherical grains and, therefore, not applicable to undisturbed materials of varying texture and with possible structural influences.

4.2.5. Geometrical models

Hilfer (2000) evaluated the scale-dependent characterisation of the microstructure in porous or heterogeneous media to predict transport parameters. The author summarises – at the hand of reference to numerous authors involved in such modelling exercises – capillary tube and slit models, grain models, network models, percolation models, fractal models, stochastic reconstruction models and diagenetic models.

Pore network analyses were conducted by Tsakiroglou and Fleury (1999) and included microscopic parameters such as pore geometry, pore-size distribution, pore space topology and fractal roughness. The authors supply a detailed review of the resistivity index, as well as the development of percolation theory applied to transport in disordered media. A dynamic pore-scale network model was also reviewed and applied by Hassanizadeh et al. (2002). Earlier work by Giménez et al. (1997) reviewed the most important fractal models for predicting soil hydraulic properties, including the Cantor bar, Kock curve, Sierpiński carpet and Menger sponge. Vita (2011) evaluated specifically the Menger's Sponge model of porosity (essentially a three-dimensional depiction of Sierpiński carpet scheme) with the aim of improving accuracy by modelling towards infinitesimal pores. Although not the detail covered in this paper, the two-dimensional Sierpiński carpet scheme showing the principle of moving towards the infinitesimal is shown in Fig. 13.

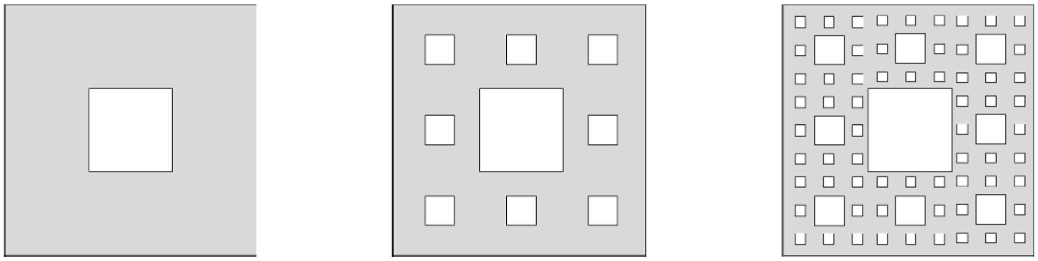

Figure 13. The Sierpiński carpet scheme to illustrate the principle of infinitesimal pores (adapted from Vita 2011).

A numerical comparison between the equivalent continuum (EC), non-homogeneous or discreet fracture (NH) and dual porosity (DP) models for flow through fractured porous media is discussed by Samardzioska and Popov (2005). Although not quantifying porosity per se, the paper evaluated the simplifications of natural porous systems to conceptual systems, which represent the natural system most accurately. This conceptualisation is shown in Fig. 14.

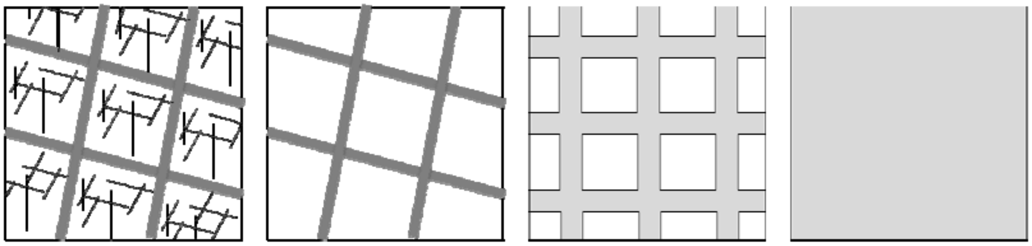

Figure 14. Grey denoting pore space and white matrix blocks for, from left to right, the natural fractured porous medium, followed by the non-homogeneous, dual porosity and equivalent continuum representations (adapted from Samardzioska and Popov 2005).

Upscaling of porous media (what the statistical distribution of a set of properties at a small scale says about the statistics of the same property at a larger scale) has been addressed to various levels of detail by a number of authors, of which the mathematical derivations are detailed in the respective studies (e.g. Hunt 1998; Guéguen et al. 2006; Hunt 2004; Hunt and Gee 2002; Pickup et al. 2005; Pickup and Hern 2002; Taggart 2002). Fractal analyses were also considered by many of these authors, assuming proportionality between pore radii and particle radii to generate water-retention curves, and also because of the lack of assumption of statistical homogeneity.

A three-dimensional geometrical-topological system of intersecting ellipsoids was generated from three-dimensional information of pore space by Yanuka et al. (1985). Neck (throat) radii were calculated from overlapping ellipsoids for simple cubic, orthorhombic and rhombohedral packing, as well as for glass beads and sandstone. More recently, Youngs (2008) considered steady water flow, also through cubic and tetrahedral (rhombohedral) packing, via modelling soil aggregates as uniform spheres.

Local porosity distributions and percolation probabilities were applied to yield a scale dependent characterisation of the microstructure in porous media with the aim of quantifying transport. A detailed review on characterisation of geometric observables and application to microstructure specifically are detailed by Hilfer (2002).

4.2.6. Changing porosity (consolidation and swell)

A number of authors have recently considered the movement of moisture through cracked clays. Murad and Cushman (1997) and Murad and Moyne (2008) consider expansive clays as a dual-porosity system whereby the swelling medium is considered on three scales, viz. nano- (clay polarity, or submicro- as per previous literature), micro- (clay clusters) and macro-scale (dual-porosity system), resulting in multiscale electro-chemo-mechanical modelling of expansive soils (Fig. 15). Fredlund et al. (2010) elaborate on the commencement of cracking in clayey soils from ground surface with increasing matric suction. They evaluate the soil-moisture characteristic curves for intact clay, cracked soil mass and finally the cracked portion alone. This accentuates the importance of considering changing porosity in natural materials with changing moisture content.

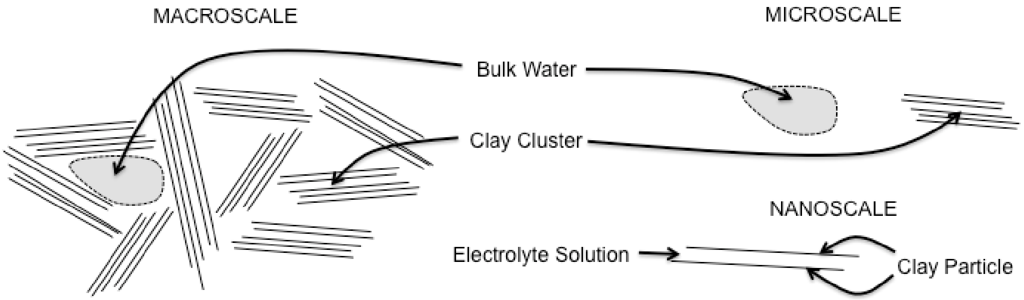

Figure 15. Three-scale clay model (adapted from Murad and Cushman 1997; Murad and Moyne 2008).

Another study considered the changes in suction with associated shrinkage of swelling clays in terms of constant porosity approaches (although not theoretically viable as porosity should change with shrinkage) and geometrical similar shrinkage approaches (Gregory et al. 2010).

Swelling and shrinkage occur depending on moisture content. Consolidation, however, is a function of applied load and may result in a more permanent change in porosity. The quantification thereof is discussed in detail by Bear and Cheng (2010) who consider it important as deformation affects the water storage and may result in surface subsidence. This was further evaluated by, for instance, Moosavi et al. (2012), who considered the change in porosity due to pore volume compression.

4.3. Relating porosity to hydraulic parameters

Numerous empirical methods exist to correlate porosity to hydraulic conductivity. Selected recent applications and developments include (in alphabetical order):

- Aimrum et al. (2004) evaluated saturated hydraulic conductivity in paddy soils applying Kozeny's equation.
- Dexter (2004) used the slope of the soil water retention curve at its inflection point.
- Dexter and Richard (2009) applied a multi-exponential water retention function and Marshall's capillary tube approach to freshly tilled soils.
- Flint and Selker (2003) evaluated hydraulic conductivity of volcanic tuffs from the Yucca Mountain using the Kozeny-Carman equation.
- Jarvis et al. (2002) considered available soil information (including effective porosity and grading curves) to quantify hydraulic conductivity, concluding that a major issue remaining is variations in pore structures and that direct methods may still be more reliable.
- Kutílek (2004) considered soils with bimodal pore distribution (matrix and structural pores) and related these soil structural properties to soil hydraulic properties.
- Lipiec et al. (2006) evaluated soil porosity and water infiltration influenced by tillage methods.
- Neuman (2005) reviewed and evaluated the directional dependence of advective porosity (effective porosity to flow) specifically applied to tracers.
- Podgorney and Fairley (2008) investigated episodic flow from unsaturated porous media into a single vertical macropore of known dimensions, noting that consideration of possible permeable pore walls, hysteresis in the pore due to varying diameter and film flow is required.
- Vervoort and Cattle (2003) determined saturated hydraulic conductivity from the model based on lognormal pore size distribution by Kosugi. They focussed specifically on incorporating tortuosity (crookedness of flow path) and lack of connectivity.

5. Case Studies

5.1. Temporary hillslope wetland on Lanseria Gneiss

5.1.1. Materials and methods

The case study is situated in Midrand (South Africa) and is underlain by tonalitic gneiss of the Lanseria Gneiss (Johannesburg Granite Dome). Extensive excavation has commenced at the site followed by the identification of a temporary hillslope wetland. Although the wetland has been destroyed in the process, a 200 m long downslope view to depths ranging between 2 m and 8 m make the study of these systems possible.

Methods employed include the collation of historical data (comprising 23 test pit descriptions prior to construction for the initial geotechnical studies of the site and the site upslope on the hill crest, as well as all associated sample results of soil grading, hydrometer and Atterberg limits), logging of 16 additional profiles through the exposed section and sampling of each different horizon. Soil profiles were recorded according to the draft SANS 633 (SABS 2009), evaluating soil moisture, colour, consistency, soil structure, soil type and origin. Laboratory analyses included – for each horizon at distinct points down the slope – soil grading, hydrometer, Atterberg limits, X-Ray Fluorescence Spectroscopy (XRF) and X-Ray Diffraction (XRD).

5.1.2. Results

A vast amount of data has been generated during the course of the study, significant portions of which is presently under review (Dippenaar et al. 2013). The scope of the inclusion in this paper is to emphasise the proper understanding of porosity as a fundamental parameter in understanding special flow systems.

The typical soil succession for four positions along the slope (hillcrest, upper slope, midslope and lower slope) have been simplified to emphasise important aspects and are as follows:

- Colluvium at surface, typically well leached and predominantly sandy in texture; often pinholed or voided
- Ferricrete (nodular to hardpan) in the pebble marker horizon or the residual granite; notably absent on the hillcrest and midslope)
- Residual granite, distinctly mottled in a silty gravelly sandy soil
- Completely weathered granite, occasionally mottled in a sandy gravelly soil exhibiting original rock joints
- Weathered and fractured granite bedrock with distinct Fe-precipitation evident on joint planes.

Porosities were calculated based on density relationships and according to the empirical approach of Istomina (1957) as shown comparatively in Fig. 16. Mineral densities were taken as follows (Deer et al. 1996):

- Alkali feldspar (K to Na): 2 550 – 2 630 kg/m^3
- Na plagioclase: 2 620 kg/m^3
- Ca plagioclase: 2 760 kg/m^3
- Quartz: 2 650 kg/m^3
- Hematite: 5 254 kg/m^3
- Gibbsite: 2 400 kg/m^3
- Goethite: 4 300 kg/m^3
- Kaolinite: 2 680 kg/m^3.

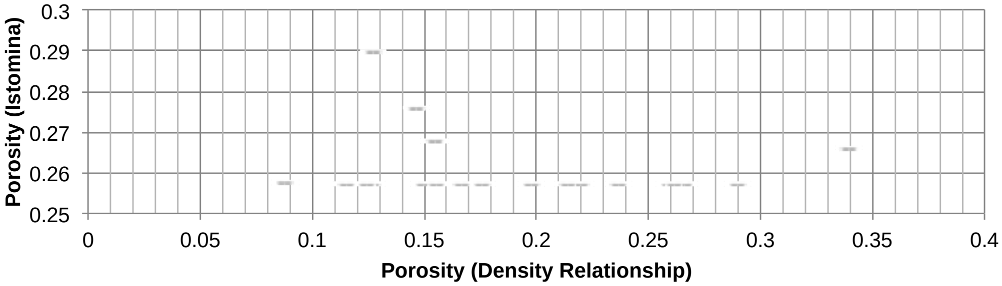

Figure 16. Porosity calculated through density relationships compared to those calculated according to Istomina for a temporary hillslope wetland underlain by granite.

Much more pronounced variation in porosity according to density relationships are evident with the more porous soil horizons being the ferricrete and residual granite. Calculated values of porosity range between 0.15 and 0.23 for transported soils, 0.26 and 0.31 for ferricrete and residuum, and 0.11 and 0.14 for weathered granite. The results are validated by visual seepage from the ferricrete horizon where porosity is not only high, but pore spaces are generally large to allow free drainage (Fig. 17).

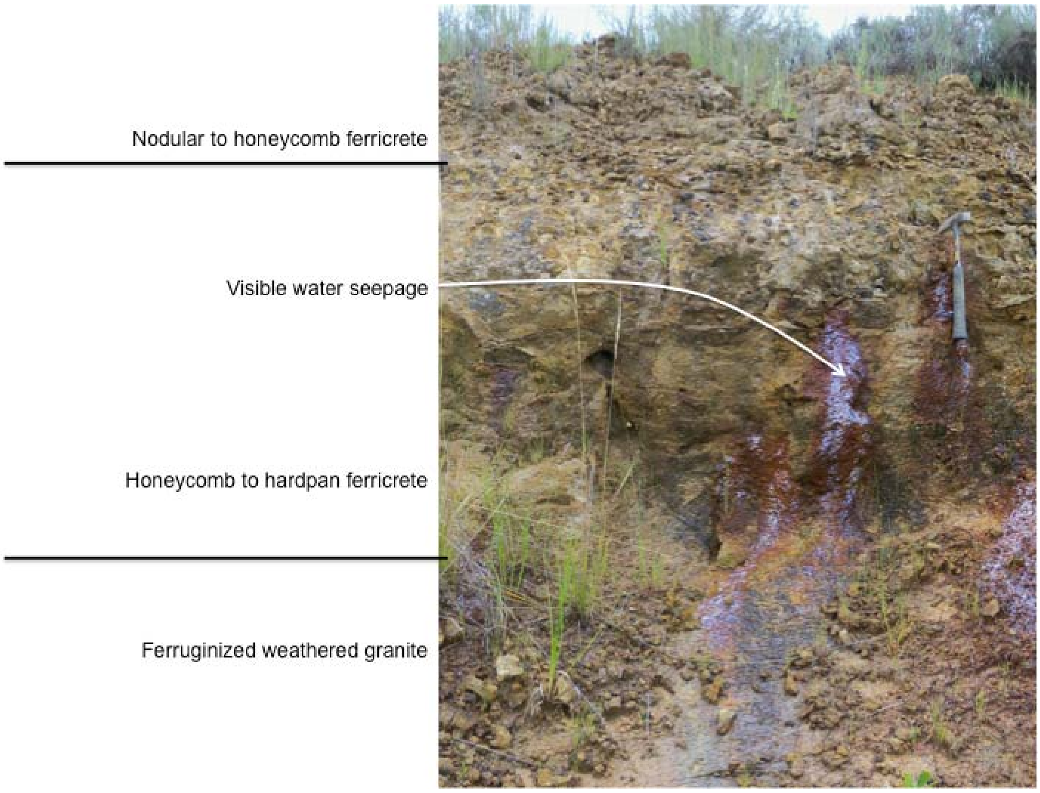

Figure 17. Seepage from ferricrete in a temporary hillslope wetland underlain by granite.

The system can be classified vertically as follows:

- Surface (transported) materials, zone of infiltration and leaching
- Ferricrete, high porosity and zone of interflow with elevated anticipated hydraulic conductivity

- Bedrock, low porosity resulting in low storage with limited vertical flow through open fractures, if present, and distinct precipitation of Fe-minerals on joint planes, indicating the periodical presence of water.

6. Conclusions

Porosity applied to vadose zone hydrological investigations should include

1. Specification of the type of porosity and the medium, namely primary, secondary or tertiary, and whether in soil or rock
2. Evaluation of the different scales of porosity, including submicro, micro, meso and macro, and accounting for multi-scale systems and including all heterogeneity and anisotropy
3. Understanding of the effective porosity as well as the non-effective porosity which may still influence consolidation, cracking and subsidence
4. Water saturation to address the ability of the void space to store and transmit water, as well as to understand the different hydraulic conductivities at different moisture contents.

An exposed temporary hillslope wetland on Archaean gneiss was used to illustrate the importance of understanding basic concepts of porosity. It is hoped that this paper will result in a more universal language and understanding of the concept for application in hydrology, hydrogeology, engineering, soil science and related disciplines.

7. The Way Forward

Several specific issues have been identified as problematic when determining porosity. These are noted below and are presently being investigated further.

1. Consolidation results in a permanent change in porosity. However, seasonal wetting and drying of expansive clays result in cycles of swelling (decrease in porosity) and shrinkage (leading to cracking and subsequently increase in porosity). Some definable moisture content should govern this process and, if quantifiable, will aid in the understanding of when clays are porous and when clays serve as low permeability barriers. Large cracks are generally non-capillary and induce flow, whereas expanded or consolidated clays are highly capillary despite the potential of being highly porous as well.
2. Fractures are variable in terms of (a) spacing and directions of different joint sets, (b) apertures and (c) the influence of weathering and precipitation on the continuity thereof. Straightforward fracture porosity is therefore not straightforward to estimate and the notable difficulty arises when considering fractured vadose zone.
3. Leaching processes may result in, for instance, collapsible soil fabric where the material is at a density well below that of densest packing with large non-capillary pore spaces highly prone to rapid consolidation (collapse). With the clay leaching from these horizons, the horizon below such a horizon is often enriched in clay (notably kaolinite) which may result in perching of water, further exacerbating the influence of moisture on the soil, notably as a triggering mechanism of collapse under load.

Although numerous advances on the quantification of porosity are evident in recent literature, special emphasis is required for selected case studies such as the above.

8. Acknowledgements

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