BIO-INSPIRED PARTICULATE FILTERS

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The filtration of particulates through a porous medium is controlled by particle-level forces and geometrical constraints (e.g., pore throat -to- migratory particle size ratios). A comparison between biological filters found in living organisms and mineral filters found in the geo-environment suggests the manipulation of material parameters for filtration control.

Keywords: Fines migration, filters, rubber chips, pore throat control

BIOFILTERS

Filters found in living organisms are innately selective: the relevant bio-structure controls the migration of particular species through its filter walls. The filter walls are thus considered flexible and the degree of flexibility is controlled by electrochemical effects. A living cell, for example, contains a flexible (selective) filter wall called plasma membrane. Transmembrane proteins present across the plasma membrane form water-filled channels through which ions migrate by diffusion across the otherwise impermeable membrane (Figure 1a). The opening of these channels may be triggered by the attachment of signaling molecules or ligands, mechanical excitations (e.g., sound waves), and/or voltage drops across the plasma membrane (Kimball, 1994). Kidneys and the skin are additional examples of more complex electrochemically-driven biofilters containing flexible filter walls.

GEOFILTERS

Filters found in the geo-environment (e.g., geofilters) are typically composed of soil particles. Applications include protective filters for earth dams and retaining structures, sand filters for wastewater treatment, and gravel pack in oil production operations. Geofilter walls are rigid because mineral particles have high stiffness. The migration of particles through the filter is ultimately controlled by geometrical constraints (i.e., pore throat sizes) and interactions between migrating particles, pore walls, and the pore fluid. The pore throat size can be described by the diameter of the largest spherical particle that can pass through the pore throat, d_{max} (Figure 1b). Particle concentration is important, as particles can interact to form bridges on pore throats that are larger than a single particle. The maximum pore throat -to- migratory particle size ratio d_{max}/d for which bridging is attainable depends on particle concentration, shape, surface roughness, and flow conditions (Valdes, 2002).

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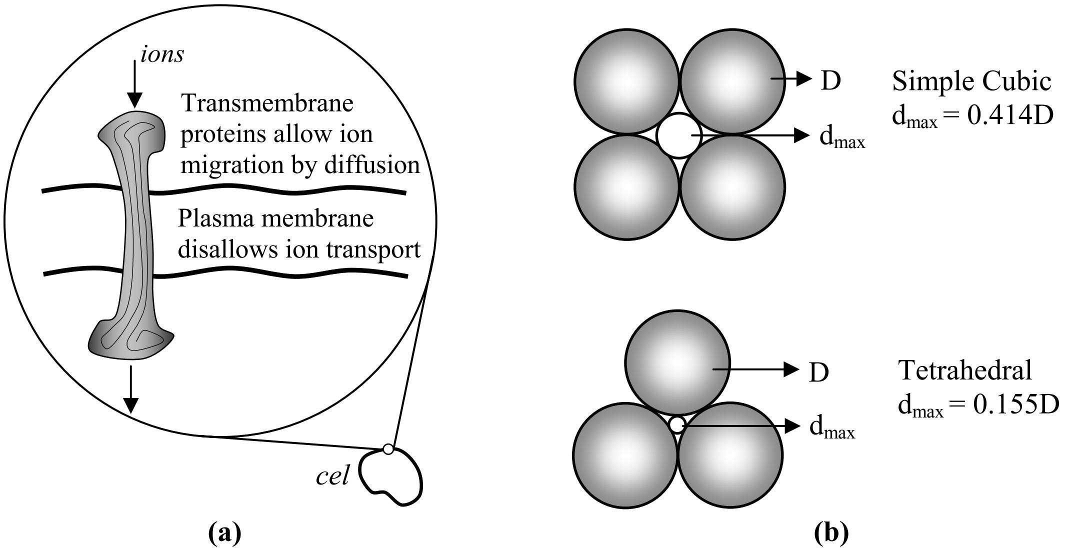

Figure 1. Filtration and passage. (a) Ions through cell walls. (b) Pore throat sizes (i.e., diameter of largest spherical particle that can pass through the pore throat) for simple cubic and tetrahedral packings.

The selection of geofilter material involves the optimization of filter particle size. Current geotechnical filter criteria emerge from empirical considerations derived from macroscale experimental testing and are based on particle retention by size exclusion (Sherard et al., 1984; Bonala and Reddi, 1998):

$$\frac{D_{15}}{d_{85}} < 5 \quad \textit{for particle retention} \qquad \frac{D_{15}}{d_{15}} \geq 5 \quad \textit{for adequate permeability}$$

The subscripts describe percent finer by weight. Other filter criteria consider pore throat sizes more directly (i.e., controlling constriction size concept - Kenney et al., 1985).

FILTRATION CONTROL

Filtration in particulate materials can be controlled by altering pore throat -to- migratory particle size ratios or by manipulating particle level forces to enhance or hamper entrapment. Controlling these parameters translates to controlling the filtration capabilities of a particulate matrix, much like a living cell controls the passage of certain species through its cell walls.

Geometrical Constraints – Novel Approach

Pore throat size is related to the packing of the particulate matrix in the case of granular materials (Figure 1b). The filtration ability of a particulate medium can thus be regulated by rearranging particles into different packings, thus altering the pore throat size. A novel approach invokes the selective nature of biofilters: in this case, pore-throat sizes can be altered by external forces. Consider a particulate matrix consisting of low-stiffness, flexible material (e.g., rubber chips - the high stiffness of standard filter sand renders stress-controlled filtration unproductive). Particle contacts are flattened upon the application of stresses, thus reducing pore throat sizes. Figure 2 shows the reduction in pore throat size for systems of flexible spherical particles with increasing vertical strain ε for isotropic and zero-lateral-strain conditions. The analysis is based on geometry only. A vertical strain of 15 percent in one-dimensional compression induces pore throat size reductions of 25 and 50 percent for simple cubic and tetrahedral packings, respectively. Vertical strains of 15 percent are readily achievable with stresses on the order of 25 kPa for rubber chips ($C_u = 1.5$; $D_{50} = 0.7$ mm) in one-dimensional compression (Liang, 2003).

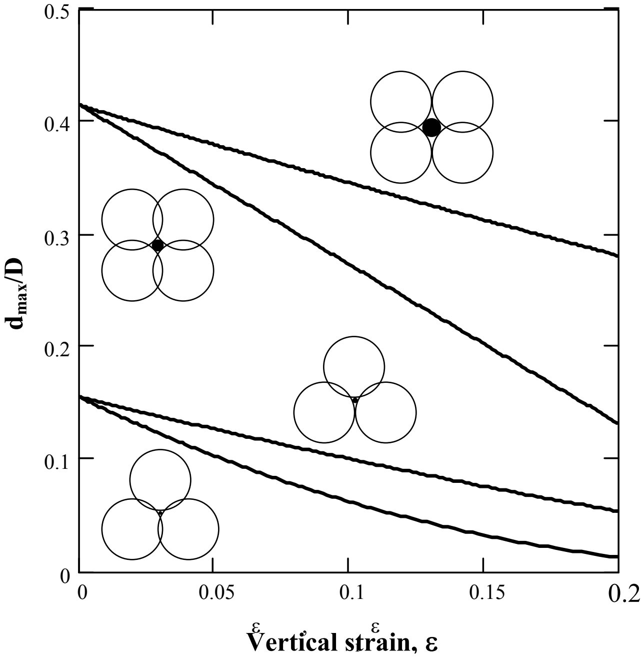

Figure 2. Reduction in pore throat size d_{max} for deformable spherical particles with increasing vertical strain ε in isotropic and one-dimensional compression (simple cubic and tetrahedral packings).

Particle Level Forces

Migratory particles are initially held in place by electrical adhesion forces and self-weight: a minimum drag force or net electric repulsion is required for their detachment (Sharma et al., 1992). The manipulation of particle-level forces can render controlled filtration. Figure 3 shows a comparison between drag, buoyant weight, and van der Waals attraction forces acting on a spherical silica particle of diameter d in water (laminar flow). For the conditions considered, the migration of particles with $d \leq 20\mu m$ is governed by electrical forces, in turn determined by pore fluid and particle characteristics. For $d \leq 20\mu m$, particle entrapment can be controlled by reducing double layer repulsion through fluid chemistry control: the velocity required for drag-induced fines migration increases as van der Waals attraction forces prevail (as shown by the arrow in Figure 3). In general, particle -to- pore wall attraction forces overcome electrical repulsion at extreme pH or near the isoelectric point and at high ionic concentration, whereas net repulsion occurs at pH away from the isoelectric point and at low ionic concentration (McDowell-Boyer, 1992).

FINAL REMARKS

The effectiveness of selective (i.e., flexible) filter walls found in biofilters offers a novel approach to particulate filtration for engineering applications. The rigid wall nature of mineral particle filters is overcome by the use of low stiffness filter particles (e.g., rubber chips) that deform readily with the application of external forces, in turn enabling filtration control through pore throat size manipulation. Moreover, particle level forces can be altered by changing the pore fluid chemistry, thus enhancing attraction or repulsion forces. Controllable particulate filters may gain relevance as new geotechnical filters (i.e., piping and clogging control), waste water filters (i.e., improved filter de-clogging), and gravel pack filtration (i.e., sand control).

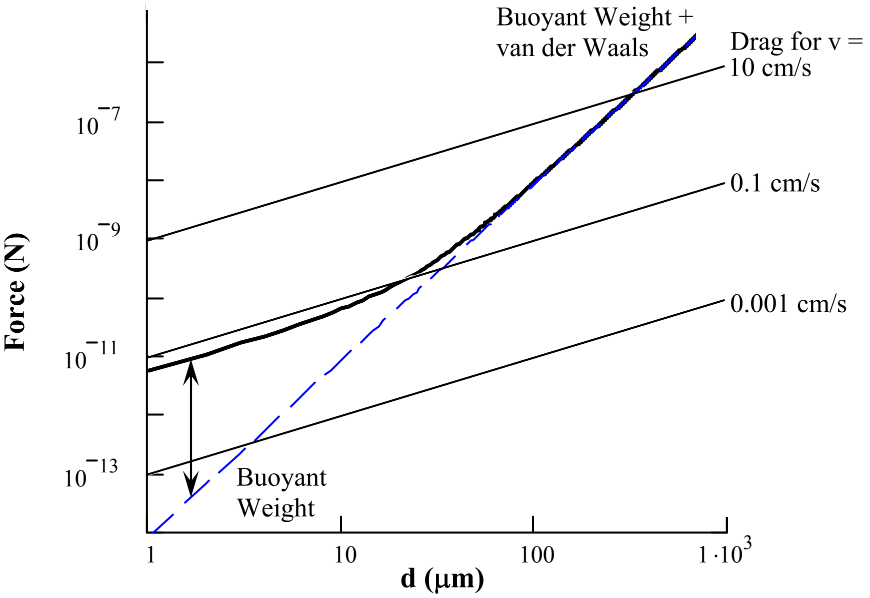

Figure 3. Drag, buoyant weight, and van der Waals attraction forces for spherical particles in water.

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