Comment on "Transport and fate of bacteria in porous media: Coupled effects of chemical conditions and pore space geometry" by Saeed Torkzaban et al.

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[1] The article by *Torkzaban et al.* [2008] provides interesting data supporting the expectation that a significant fraction of colloids (bacterial cells in this case) are retained in porous media without actual attachment to collector surfaces. However, the authors present a theoretical approach that warrants elaboration regarding its relationship to previously existing approaches.

[2] The theoretical analyses provided by the authors involved a balance of the driving and resisting torques acting on an immobilized colloid to determine whether rolling (and by extension detachment) of the colloid would be initiated, as described in previous articles [e.g., *Hubbe*, 1984, 1985; *Bergendahl and Grasso*, 2000; *Li et al.*, 2005]. In this approach, the contact area between the colloid and the surface (its radius) provides a lever arm, which along with the adhesion force comprises the torque that resists detachment (Figure 1). A torque driving detachment is generated by fluid drag acting at a point somewhat above the centroid of the colloid (1.399 $\times$ colloid radius) [*Sharma et al.*, 1992]. This torque balance has been traditionally applied to colloids immobilized to surfaces, i.e., in traditional parlance, where the colloid has overcome any repulsive energy barrier, and has come into physical contact with the surface (Figure 1). For colloids that overcome the energy barrier, the adhesive torque typically dominates, and the colloid is typically considered irreversibly attached (a perfect sink boundary).

[3] *Torkzaban et al.* [2008] and previously *Torkzaban et al.* [2007] have applied this particular torque balance in the context of colloids associated with surfaces via secondary energy minima. They approximate the adhesion force with the attractive force experienced in the secondary energy minimum interaction; whereas previous approaches have approximated the adhesion force with the stronger attractive force experienced in the primary energy minimum (Figure 2).

[4] The approach of *Torkzaban et al.* [2007, 2008] deserves further discussion because previously published force and torque balances for secondary energy minimum associated colloids allow translation in response to net forces (fluid drag, diffusion, gravitation, van der Waals, and electric double layer) as well as spinning in response to fluid shear [*Rajagopalan and Tien*, 1976; *Prieve and Lin*, 1980; *Yang et al.*, 1998; *Johnson et al.*, 2007]. The latter is built into the force balance by way of hydrodynamic retardation coefficients [e.g., *Rajagopalan and Tien*, 1976; *Johnson et al.*, 2007]. This approach is taken with the expectation that the energy barrier between the surface and the secondary energy minimum prevents physical contact between the colloid and stationary surface, such that the friction resisting colloid motion emanates from the fluid viscosity rather than emanating from adhesive contact between the colloid and the surface (Figure 3).

[5] The major difference in treatment of secondary energy minimum associated colloids in the traditional approaches versus that invoked by *Torkzaban et al.* [2007, 2008] is the source of friction that resists colloid motion. In the traditional approach, the colloid has no adhesive contact with the surface, and friction emanates from the viscosity of the fluid in which the colloid translates and rotates; whereas

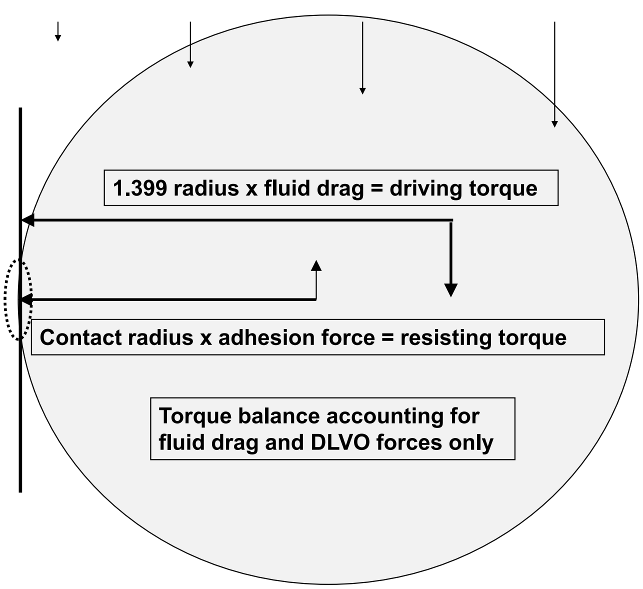

Figure 1. Schematic of colloid attached to surface with corresponding driving torque (driving detachment) originating from fluid drag (depicted by arrows at top) and resisting torque (resisting detachment) originating from adhesion.

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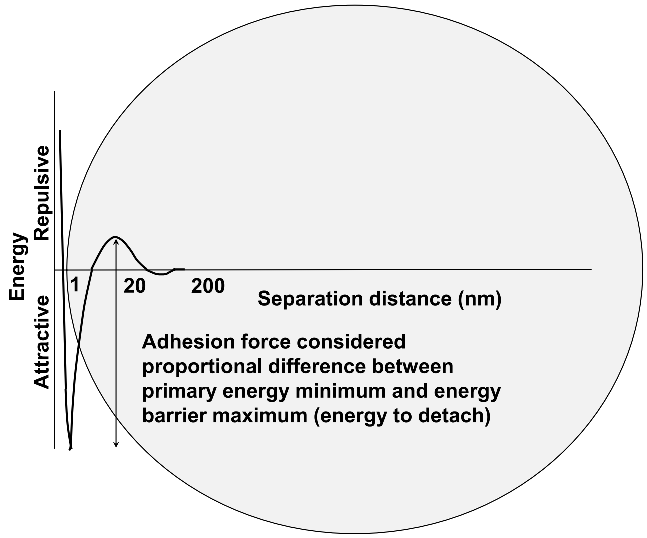

Figure 2. Schematic of colloid-surface interaction force profile superimposed on colloid of ~800 nm diameter associated with the surface via the primary energy minimum.

in the approach by *Torkzaban et al.* [2007, 2008], friction emanates from adhesive contact between the colloid and the surface, and colloid translation is assumed to not occur.

[6] A great deal of experimental data can be cited that implicates retention of colloids in secondary energy minima. The issue we raise is not whether retention of secondary energy minimum associated colloids occurs, but rather, how it occurs. Our own simulations using a traditional force and torque balance for secondary energy minimum associated colloids show that colloids may be retained in zones of low fluid drag at the pore scale even without adhesive contact with the surface [*Johnson et al.*, 2007]. In our model, retention without attachment occurred in rear stagnation zones, although these represent just one possible type of zone of low fluid drag. Torkzaban and colleagues appear to incorrectly assume that retention without attachment occurs only in flow vortices. It must be noted that complete flow stagnation is not necessary to produce colloid retention; rather, only sufficiently low fluid drag and sufficiently high secondary energy minimum attraction are required to produce retention, and this retention occurs without attachment [*Johnson et al.*, 2007], as opposed to primary energy minimum associated colloids (e.g., via heterogeneity and wedging), which are genuinely attached. There are two important points here: (1) retention of secondary energy minimum associated colloids can be simulated in a system where colloid spinning and translation are allowed, and (2) spinning of the colloid in response to fluid shear does not necessarily lead to reentrainment. These two points, demonstrated by *Johnson et al.* [2007] for secondary energy minimum associated colloids, contrast with the assumptions used by *Torkzaban et al.* [2007, 2008] that (1) colloids may be immobilized by secondary energy minimum interaction; that is, secondary energy minimum interaction constitutes adhesive contact with the surface, and (2) the initiation of rolling can be equated to reentrainment.

[7] That physical contact is established when a colloid associates with a surface via the primary energy minimum is quite clear, since the equilibrium separation distance is close to 0.16 nm [*Israelachvili*, 1992], where Born repulsion results from the overlap of electron orbitals on the two surfaces. In contrast, the secondary energy minimum involves separation distances of ten to hundreds of nm, and the notion of contact is much less clear. Adhesion theory [e.g., *Johnson et al.*, 1971; *Derjaguin et al.*, 1975] supposes physical contact between the colloid and the surface, incorporating some degree of physical deformation of the colloid and the surface via Young's moduli and Poisson ratios to yield an adhesive contact area [see *Bergendahl and Grasso*, 2000], such that the friction

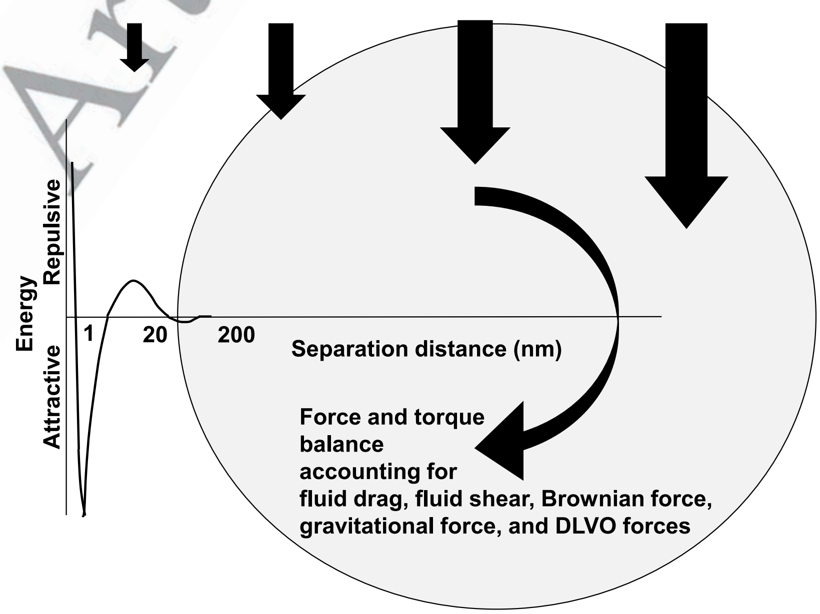

Figure 3. Schematic of colloid-surface interaction force profile superimposed on colloid of ~800 nm diameter associated with the surface via the secondary energy minimum. Arrows depict fluid drag force and associated torque.

resisting colloid motion emanates from the colloid-surface contact. The corresponding equation for contact radius provided by *Torkzaban et al.* [2007, 2008] was obtained by manipulation of equations for the contact radius and pull-off force provided by *Israelachvili* [1992, chapter 15]. That source clearly states that the equations apply to materials in adhesive contact. Although secondary energy minimum interactions (weak van der Waals) occur over definable areas on the colloid and collector surfaces [*Israelachvili*, 1992], the friction resisting colloid motion in secondary energy minima has traditionally been considered to arise from the colloid-fluid interface (fluid viscosity). *Torkzaban et al.* [2007, 2008] depart from this traditional approach, and equate secondary energy minimum to adhesive contact, a move that warrants further discussion and exploration. This comment provides an opportunity for Torkzaban and colleagues to substantiate their stance that adhesion parameters developed for contact are applicable to secondary energy minimum interactions.

References

Bergendahl, J., and D. Grasso (2000), Prediction of colloid detachment in a model porous media: Hydrodynamics, *Chem. Eng. Sci.*, *55*(9), 1523–1532, doi:10.1016/S0009-2509(99)00422-4.

Derjaguin, B. V., V. M. Muller, and Y. P. Toporov (1975), Effect of contact deformation on the adhesion of particles, *J. Colloid Interface Sci.*, *53*, 314–326, doi:10.1016/0021-9797(75)90018-1.

Hubbe, M. A. (1984), Theory of detachment of colloidal particles from flat surfaces exposed to flow, *Colloids Surf.*, *12*, 151–178, doi:10.1016/0166-6622(84)80096-7.

Hubbe, M. A. (1985), Detachment of colloidal hydrous oxide spheres from flat solids exposed to flow, *Colloids Surf.*, *16*, 249–270, doi:10.1016/0166-6622(85)80257-2.

Israelachvili, J. N. (1992), *Intermolecular and Surface Forces*, 2nd ed., Academic, London.

Johnson, K. L., K. Kendall, and A. D. Roberts (1971), Surface energy and the contact of elastic solids, *Proc. R. Soc. London A*, *324*, 301–313, doi:10.1098/rspa.1971.0141.

Johnson, W. P., X. Li, and G. Yal (2007), Colloid retention in porous media: Mechanistic confirmation of wedging and retention in zones of flow stagnation, *Environ. Sci. Technol.*, *41*, 1279–1287, doi:10.1021/es061301x.

Li, X., P. Zhang, C. L. Lin, and W. P. Johnson (2005), Role of hydrodynamic drag on microsphere deposition and re-entrainment in porous media under unfavorable conditions, *Environ. Sci. Technol.*, *39*, 4012–4020, doi:10.1021/es048814t.

Prieve, D. C., and M. M. J. Lin (1980), Adsorption of Brownian hydrosols onto a rotating disc aided by a uniform applied force, *J. Colloid Interface Sci.*, *76*, 32–47, doi:10.1016/0021-9797(80)90268-4.

Rajagopalan, R., and C. Tien (1976), Trajectory analysis of deep bed filtration with the sphere-in-cell porous media model, *AIChE J.*, *22*, 523–533, doi:10.1002/aic.690220316.

Sharma, M. M., H. Chamoun, D. S. H. Sita Rama Sarma, and R. S. Schechter (1992), Factors controlling the hydrodynamic detachment of particles from surfaces, *J. Colloid Interface Sci.*, *149*, 121–134, doi:10.1016/0021-9797(92)90398-6.

Torkzaban, S., S. A. Bradford, and S. L. Walker (2007), Resolving the coupled effects of hydrodynamics and DLVO forces on colloid attachment in porous media, *Langmuir*, *23*(19), 9652–9660, doi:10.1021/la700995e.

Torkzaban, S., S. S. Tazehkand, S. L. Walker, and S. A. Bradford (2008), Transport and fate of bacteria in porous media: Coupled effects of chemical conditions and pore space geometry, *Water Resour. Res.*, *44*, W04403, doi:10.1029/2007WR006541.

Yang, C., T. Dabros, D. Li, J. Czarnecki, and J. H. Masliyah (1998), Kinetics of particle transport to a solid surface from an impinging jet under surface and external force fields, *J. Colloid Interface Sci.*, *208*, 226–240, doi:10.1006/jcis.1998.5806.

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