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Research papers

Non-monotonic permeability variation during colloidal transport: Governing equations and analytical model

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ABSTRACT

Permeability decline associated with the migration of natural reservoir fines impairs the well index of injection and production wells in aquifers and oilfields. In this study, we perform laboratory corefloods using aqueous solutions with different salinities in engineered rocks with different kaolinite content, yielding fines migration and permeability alteration. Unusual permeability growth has been observed at high salinities in rocks with low kaolinite concentrations. This has been attributed to permeability increase during particle detachment and re-attachment of already mobilised fines by electrostatic attraction to the rock in stagnant zones of the porous space. We refine the traditional model for fines migration by adding mathematical expressions for the particle re-attachment rate, particle detachment with delay relative to salinity decrease, and the attached-concentration-dependency of permeability. A one-dimensional flow problem that accounts for those three effects allows for an exact analytical solution. The modified model captures the observed effect of permeability increase at high water salinities in rocks with low kaolinite concentrations. The developed model matches the coreflooding data with high accuracy, and the obtained model coefficients vary within their usual intervals.

1. Introduction

Detachment and straining of suspension-colloidal particles during flow in natural reservoirs and engineered porous media occur in numerous natural and technological processes in environmental, chemical, and petroleum engineering, as well as in geology. Some of the primary applications include drilling fluid invasion into subsurface formations, propagation of viruses and bacteria in subterranean waters, storage of fresh or hot water in aquifers, migration of fines in the vadose zone, irrigation of plants, industrial filtering, waste disposal in aquifers and water waste management, water injection into oilfields, re-injection or disposal of produced water in oilfields and aquifers, and size-exclusion chromatography (Civan, 2007; Kaplan and Muñoz-Carpena, 2014; Tiab and Donaldson, 2015; Zhang et al., 2015, 2016). Detachment and straining of suspension-colloidal particles with consequent variation in rock permeability yield significant hydraulic flux changes for the above-mentioned processes (Bradford and Bettahar, 2005; Bradford et al., 2003; Bradford and Torkzaban, 2008; Chrysikopoulos and Syngouna, 2014; Katzourakis and Chrysikopoulos, 2015; Syngouna and Chrysikopoulos, 2011; Yakirevich et al., 2013; Yu et al., 2012; Yuan et al., 2016).

The most common predictive tool to manage and optimise the above processes is laboratory-based mathematical modelling. Determining the particle exchange rate and formation damage coefficients from laboratory corefloods or column tests, upscaling these values, and then using them in predictive modelling allows for successful drilling fluid loss control, geophysical interpretation of drilling fluid invasion profiles, forecasting of aquifer contamination, design of water filtration or treatment technologies for environmental protection, water resource management, injected and disposed water management in oilfields, and management of production and injection artesian wells (Civan, 2007; Hayek, 2014, 2015; Tiab and Donaldson, 2015).

A schematic of particle arrangement in the pore space, including suspended particles in the carrier water and attached, strained, and re-attached fine particles at the liquid-matrix interface, is shown in Fig. 1a. Here σ_a and σ_s are the concentrations of attached and strained particles, respectively, defined as the number of attached and strained particles per unit of rock volume. The concentration c of suspended particles is defined as the number

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Nomenclature

c	Suspended particle concentration, m^{-3}
C	Dimensionless suspended particle concentration
F_d	Drag force, N
F_e	Electrostatic force, N
F_g	Gravitational force, N
F_l	Lift force, N
J	Impedance
k	Permeability, m^2
L	Core length, m
l_n	Normal lever arm, m
l_d	Drag lever arm, m
p	Pressure, Pa
P	Dimensionless pressure
S_a	Dimensionless attached particle concentration
S_s	Dimensionless strained particle concentration
$\varDelta S_{cr}$	Dimensionless mobilised concentration of detached particles
t	Time, s
T	Dimensionless time
T_0	Intersection of characteristic line and the T axis
U	Darcy's velocity, $m.s^{-1}$
U_s	Particle velocity, $m.s^{-1}$
x	Linear coordinate, m
X	Dimensionless linear coordinate

Greek symbols

α	Drift delay factor
β_a	Formation damage coefficient for attached particles
β_s	Formation damage coefficient for strained particles
γ	Salinity, $mol.m^{-3}$ $(\times 10^{-3})$
ε	Dimensionless delay time
λ	Filtration coefficient for re-attachment, m^{-1}
λ_s	Filtration coefficient for straining, m^{-1}
$\varLambda$	Dimensionless filtration coefficient for re-attachment
$\varLambda_s$	Dimensionless filtration coefficient for straining
μ	Dynamic viscosity, $Pa.s$
σ_{cr}	Maximum retention function, m^{-3}
$\varDelta\sigma_{cr}$	Mobilized concentration of detached particles with salinity decrease, m^{-3}
σ_a	Concentration of attached particles, m^{-3}
σ_s	Concentration of strained particles, m^{-3}
τ	Delay time of particle release, s
ϕ	Porosity

Subscripts

0	Initial value or condition

of suspended particles per unit of the pore volume. The suspended particles are transported by the carrier fluid with flux U. Fig. 1b shows the forces acting on the attached particles. Here the drag force F_d and lift force F_l act to detach the particles, whereas the electrostatic force F_e acts to maintain the particles to the rock surface. The gravitational force F_g can be either detaching or attaching depending on the particle position on the grain.

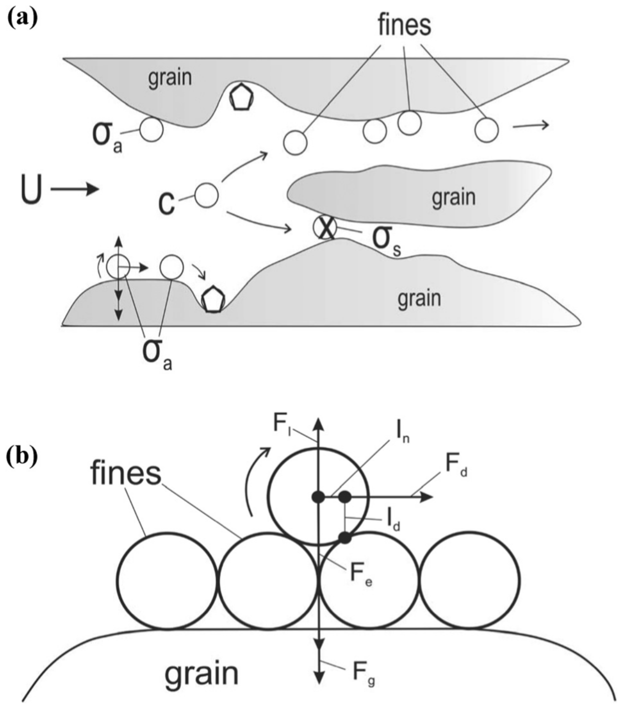

Fig. 1. Mechanical equilibrium of fines on rock surface: (a) particle detachment and straining in thin pore throats; (b) drag, electrostatic, lift, and gravitational forces acting on particles on the internal rock surface.

Two Scanning Electron Microscope (SEM) photographs of kaolinite clay fines attached to the grain surface in sandstones are presented in Fig. 2. Fig. 2a demonstrates the thin and flat shape of the kaolinite particles. As a result of their shape, attached kaolinite particles tend to have a small effect on the flow within pores. Consequently, particle detachment is not expected to result in a noticeable rise in permeability. On the contrary, plugging of a pore with a throat thinner than the leaflet cuts off the flow path, diverts the flow into other unplugged pores, increases flow tortuosity, and thus yields significant permeability reduction. Fig. 2b shows two pore throats plugged by kaolinite fines. These effects cause significant reduction of petroleum and artesian well productivity and have been widely presented in the literature (Khilar and Fogler, 1998; Muecke, 1979). Moreover, fines migration is one of the main causes for formation damage in aquifers and petroleum reservoirs (Civan, 2007).

The condition of mechanical equilibrium of a fine particle on the rock surface is an equality of the attaching and detaching torques (Bergendahl and Grasso, 2000; Bradford et al., 2013):

$$F_d(U)l_d + F_l(U)l_n = [F_e(\gamma, pH) + F_g]l_n \tag{1}$$

Here l_d and $\mathrm{l_n}$ are the tangential and normal lever arms, U is the flow velocity, and γ is the ionic strength of the injected solute. The velocity dependencies of the drag and lift forces, and the pH- and ionic-strength-dependency of the electrostatic force for fine particles in sandstones can be deduced from the explicit expressions for these forces (Bergendahl and Grasso, 2000; Derjaguin and Landau, 1941; Elimelech et al., 1995; Gregory, 1981; Takahashi and Kovscek, 2010; Torkzaban et al., 2013). It follows that increasing the flow velocity or pH, or decreasing the fluid salinity shifts the torque balance equilibrium towards particle detachment. The lever arm l_n is given by Hertz's theory and is a function of the Young's moduli and Poisson ratios of both the grain and the attached particle (Bradford et al., 2013). The torque balance equation allows determining whether any particle on the grain surface will be mobilised by the flow with velocity U, pH and salinity γ. This criterion enables the determination of the maximum attached particle