Mechanisms, Modeling, and Effect of Particulate Processes in Completion and Formation Damage

FARUK CIVAN, Ph.D.
Alumni Chair Professor
Mewbourne School of Petroleum and Geological Engineering
The University of Oklahoma
Outline

- Objectives: Obtaining simplified models for complicated particle transport processes
- Deposition and detachment of fine particles at pore surfaces
- Fines migration, aggregation, and interface transfer in multi-phase fluid systems
Bundle-of-Leaky-Capillary-Tubes Model of Porous Media
Interstitial fluid velocity
(Dupuit, 1863)

Fluid moves faster in a tortuous path

\[ \tau = L_f / L \]

\[ v_f = \tau u_f / \phi \]
Particulate processes in porous media

- Hydrodynamic mobilization
- Colloidal expulsion
- Liberation of particles by cement dissolution
- Surface deposition

- Pore throat plugging
- Internal cake formation by small particles
- Internal and external cake formation by small particles
- External cake formation by large particles
Particulate Processes

1. Pore surface processes
2. Pore throat processes
3. Pore volume processes
Salinity Shock

CSC: Critical salt concentration (Khilar and Fogler, 1983)

Civan (2000, 2001)
Particle swelling

Clay particles

Swollen clay

Water absorption

Clayey matrix

Water absorption

Swollen matrix

Graphs showing data for different studies:
- Blomquist and Portigo: $y = 2.4932x$, $R^2 = 0.9496$
- Chenevert: $y = 0.5562x$, $R^2 = 0.9871$
- Seed et al.: $y = 0.0869x$, $R^2 = 0.9973$

$-\ln(1 - a / a_i)$ vs. $t_d$

$\ln(K_{o-k} / K_{o-k,i})$ vs. $t_d$
Temperature Effect

Arrhenius Equation (wettability index)

Vogel-Tammann-Fulcher Equation (particle-particle pull-off adherence)
Temperature Shock

Gupta and Civan (1994)
Critical Mobilization Velocity

Gruesbeck and Collins (1982)

Potanin and Uriev (1991)
\[ \tau_{cr} = \frac{H}{(24dl^2)} \]

Metzner and Reed (1955)
\[ \tau = k'(4v/r_c)^n' \]
Detachment rate coefficient

(Bell, 1978, Pierres et al., 2002, Civan, 2006)

\[ k_0 = k_\infty \exp \left( \frac{xF}{k_B T} \right) \]

- \( F \): distractive force causing detachment
- \( x \): interaction length,
- \( k_B \): Boltzmann constant
- \( T \): the absolute temperature
- \( k_\infty \): pre-exponential coefficient
Critical Fines Mobilization
Interstitial Velocity

(Amaefule et al., 1987)

Forchheimer Equation

\[
\frac{\Delta p}{v} = \frac{\phi \mu L}{K} + \left( \phi^2 \rho \beta L \right) v
\]

\[ v_{cr} = ? \]
Pore Surface Deposition

\[
\frac{d\varepsilon_d}{dt} = k_d \left( \alpha + u \right) \cdot \sigma_p \phi^{2/3}
\]

\[\varepsilon_d = \varepsilon_{d_0}, t = 0\]
Colloidal Release of Particles at Pore Surface

\[ \frac{\partial \varepsilon_r}{\partial t} = - (1 + \alpha) \cdot k_r \varepsilon_p \eta \phi^{2/3} (c_{cr} - c) \]

\[ \varepsilon_r = \varepsilon_{r,0}, t = 0 \]
Hydraulic Erosion of Particles at Pore Surface

\[ \frac{\partial \varepsilon_e}{\partial t} = -(1 + \alpha) \cdot k_e \varepsilon_p \eta_e \phi^{2/3} (\tau - \tau_{cr}) \]

\[ \varepsilon_e = \varepsilon_{e_o}, t = 0 \]
Pore Throat Plugging Deposition

\[ \beta_{cr} = A \left(1 - e^{-B \text{Re}_p}\right) + C \]

\[ \text{Re}_p = \frac{c_p u D_p}{\mu \phi} \]

\[ \beta = \frac{D_t}{D_p} \]
Pore throat plugging criterion

\[ \beta = \frac{D}{D_p} \]

Perforation-to-Average Particle Diameter Ratio

\( c_p \), Particle Concentration, lb/gal

(Reynolds number could not be used due to insufficient data)
Pore Throat Plugging

\[ \frac{\partial \varepsilon_t}{\partial t} = k_t u \sigma_p \phi \]

[bridging]

\[ \varepsilon_t = \varepsilon_{t_0}, t = 0 \]

\[ k_t \neq 0 \text{ when } \beta < \beta_{cr} \]

[non-bridging]

\[ k_t = 0 \text{ otherwise} \]
Particle migration in multi-phase flow
Particles in multi-phase fluids

Gupta and Civan (1994)
Transfer of a Wetting Particle from Nonwetting to Wetting Phase

\[ \frac{dR_1}{d(t - t_1)} = -\lambda_1 R_1 \]

Wetting phase
Transfer of a Wetting Particle from Nonwetting to Wetting Phase

\[ \frac{dR_{12}}{d(t-t_{12})} = \lambda_1 R_1 - \lambda_2 R_{12} \]  

Interface

\[ \frac{dR_2}{d(t-t_2)} = -\lambda_2 R_{12} \]  

Nonwetting phase

\[ R_1 = R_1^o, \; R_{12} = R_{12}^o, \; R_2 = R_2^o, \; t = 0 \]  

Initial condition
Equation of Permeability
Power-law (Civan, 2001-2005)

\[ \sqrt{\frac{K}{\phi}} = \Gamma \left( \frac{\phi}{\alpha - \phi} \right)^\beta \]

\[ \gamma = \frac{\lambda}{4(L_b \tau)^\delta} \sqrt{\frac{c}{2\tau}} \left( \frac{C}{C} \right)^{\frac{3\delta}{D-D}} \sum_g \left( \frac{D}{D-D} \right)^\delta n \left( \frac{3-D}{D-D} \right)^\delta \]

\[ \Gamma = \gamma \left( \phi^\nu + e \right), \nu < 0 \]

\[ \nu = \frac{1}{2} \left[ \frac{d}{3} - 1 \right] \]

\[ \beta = \left( \frac{D}{D-D} \right)^\delta n \left( \frac{3-D}{D-D} \right)^\delta \]
Particle packing and porosity

Perfect packing
\[ \phi = \phi_0 - \varepsilon \]

Loose packing
\[ \phi = \phi_0 - \alpha \varepsilon^n \]
Parametric relationships

\[ \frac{\left( \beta^{-1} \right)_{\max} - \beta^{-1}}{\left( \beta^{-1} \right)_{\max} - \left( \beta^{-1} \right)_{\min}} = \left[ \frac{\Gamma_{\max} - \Gamma}{\Gamma_{\max} - \Gamma_{\min}} \right]^{C/A} \]

\[ = \left[ \frac{\phi_{\min}^v - \phi_{\max}^v}{\phi_{\min}^v - \phi_{\max}^v} \right]^{C/A} ; \; \nu < 0 \]

Data of Cinar et al., 2001 for artificially compacted NaCl salt granulates
Power-law equation (Data of Cinar et al., 2001 for artificially compacted NaCl salt granulates)

\[ y = 1.0001x \]

\[ R^2 = 0.90 \]

\[
(2\beta)^{-1} \log_{10} \left\{ \frac{K}{\phi \Gamma^2} \right\}
\]

\[ 1.0E-18 \quad 1.0E-17 \quad 1.0E-16 \quad 1.0E-15 \quad 1.0E-14 \quad 1.0E-13 \quad 1.0E-12 \quad 1.0E-11 \]

Porosity, \( \phi \), fraction

Permeability, \( K \), mD
Confusing use of volume and mass-weighted volume averages

Conventional form (Gray et al., 1993)

\[
\frac{\partial}{\partial t} \left( \varepsilon_j \rho_j \right) + \nabla \cdot \left( \rho_j \varepsilon_j \bar{v}_j \right) = q_j
\]

\( \bar{v}_j \): Mass-weighted volume average

Consistent form (Civan, 2002)

\[
\frac{\partial}{\partial t} \left( \varepsilon_j \rho_j \right) + \nabla \cdot \left( \rho_j \varepsilon_j v_j \right) = \nabla \cdot \left[ D_j \cdot \nabla \left( \varepsilon_j \rho_j \right) \right] + q_j
\]

\( v_j \): Volume average

\textbf{Equation of continuity}

\textbf{Attention!}
Plugging-Nonplugging Paths
Gruesbeck and Collins (1982)

\[ F(d) \]

Plugging Pores
Nonplugging Pores

Interconnectivity
Plugging paths with bottle-necked pore throats
Nonplugging paths with tube like pathways

\[ q \]
\[ q_{in} \]
\[ q_{np} \]
\[ q_{p} \]
\[ d \]
\[ d_{cr} \]
\[ u_{in}(t) \]
\[ u_{np} \]
\[ u_{p} \]
\[ dx \]
Stationary phases

a) Porous matrix
b) Immobile fluids and deposits
Flowing phases

a) Gas
b) Oil
c) Water
d) Particles and precipitates
Expressing Phase Flow

\[ V_j = \text{Interstitial velocity of j-phase (m/s)} \]

\[ U_j = \text{Volume flux (Darcy velocity or superficial velocity) of j-phase (m}^3\text{/m}^2\text{-s)} \]

\[ U_s = \epsilon_s V_s = \text{Solid flux and velocity (matrix)} \]

Apply Dupuit equation
j-Phase Mass Balance

\[ \frac{\partial}{\partial t} (\varepsilon_j \rho_j) + \nabla \cdot (\rho_j u_j) = \nabla \cdot (\varepsilon_j D_j \cdot \nabla \rho_j) + \varepsilon_j \mathbf{m}_j \]
J- Phase Momentum Balance (Forchheimer Equation)

\[ u_j = -\nu_j^{-1} k_{rj} \cdot N_{ndj} \cdot K \cdot \nabla \psi_j \]

\[ \nu_j = \frac{\mu_j}{\rho_j} \]

\[ N_{ndj} = \left[ I + \text{Re}_j \right]^{-1} \]

\[ \text{Re}_j = \nu_j^{-1} \left| u_j \right| \cdot K \cdot \beta \]
Flow potential and inertial flow coefficient

\[ \psi = \int_{P_0}^{P} \frac{dp}{\rho} + g \left( z - z_o \right) + \Omega \]

\[ \beta = \frac{8.91 \times 10^8 \tau}{\phi K} \]

(Liu, Civan, Evans, 1998)
Particle i Mass Balance in j-Phase

\[ \frac{\partial}{\partial t} (\varepsilon_j \rho_j w_{ij}) + \nabla \cdot (\rho_j w_{ij} u_j) = \nabla \cdot (\varepsilon_j \rho_j D_{ij} \cdot \nabla w_{ij}) + \varepsilon_j \dot{m}_{ij} \]
Particles in slurry

- Large Particles, larger than the pores of porous media, form the filter cake
- Fine Particles, smaller than the pores, migrate into and deposit within the cake and porous media
Material balance equations

\[
\frac{d}{dt} \left[ \left( r_w^2 - r_c^2 \right) \bar{e}_s \right] = 2r_c N_{p2s}^\sigma + \left( r_w^2 - r_c^2 \right) \bar{N}_{p2s}
\]

\[
\frac{d}{dt} \left[ \left( r_w^2 - r_c^2 \right) \bar{e}_{p2s} \right] = 2r_c N_{p2s}^\sigma + \left( r_w^2 - r_c^2 \right) \bar{N}_{p2s}
\]

\[
\frac{d}{dt} \left[ \left( r_w^2 - r_c^2 \right) \bar{e}_l \right] + \left( e_{p2l} \right)_{\text{slurry}} \frac{dr_c^2}{dt} = 2r_c \left( u_{\text{l}} \right)_{\text{slurry}} - 2r_w \left( u_{\text{l}} \right)_{\text{filter}}
\]

\[
-2r_w \left( u_{p2l} \right)_{\text{filter}} - 2r_c N_{p2s}^\sigma \left( r_w^2 - r_c^2 \right) \bar{N}_{p2s}
\]
Particle deposition rates

Over the cake surface (Large and small particles)

\[ R_{ps}^{\sigma} = k_d^{\sigma} \left( u_{l} c_{p1} \right)^{\text{slurry}}_{c} - k_e^{\sigma} \left( \varepsilon_s \rho_p \right)^{\text{slurry}}_{c} \left( \tau - \tau_{cr} \right) U(\tau - \tau_{cr}) \]

\[ R_{p2s}^{\sigma} = k_{d2}^{\sigma} \left( u_{l} c_{p2l} \right)^{\text{slurry}}_{c} - k_{e2}^{\sigma} \left( \varepsilon_s c_{p2s} \right)^{\text{slurry}}_{c} \left( \tau - \tau_{cr2} \right) U(\tau - \tau_{cr2}) \]

\[ \tau = k' \left( \frac{4 \nu}{r_c} \right)^{n'} \]

\[ \tau_{cr} = H / \left( 24 d l^2 \right) \]

Within the cake and filter media (Small particles)

\[ \bar{R}_{p2s} = k' a \varepsilon_s c_{p2l} - k_e \varepsilon_s c_{p2s} \]
Filter cake and filter porosity and permeability variation

- Effect of fluid drag on the cake compressibility
- Effect of fine particle deposition in the cake and formation
Porosity and permeability relationships

\[
\frac{\overline{\phi}}{\phi^o} = \left[ 1 - \alpha \left( \frac{\varepsilon_{p2s}}{\phi^o} \right)^n \right] \left[ \frac{1}{\phi^o} - \left( \frac{1}{\phi^o} - 1 \right) \left( 1 + \frac{\bar{p}_s}{p_a} \right)^\beta \right]
\]

\[
\frac{\overline{k}_c}{k_c^o} = \left( 1 + \alpha_1 \frac{\varepsilon_{p2s}}{p2s} \right)^{-1} \left( 1 + \frac{\bar{p}_s}{p_a} \right)^{-\delta}
\]
Forchheimer’s equation for non-darcy flow

\[ \frac{\partial p}{\partial r} = \frac{\mu}{2\pi h K} \frac{q}{r} + \frac{\rho \beta}{(2\pi h)^2} \left( \frac{q}{r} \right)^2 \]
Diagnostic chart for identification of flow regime

A straight line plot indicates Darcy flow

Darcy Flow
\[ y = 419.26x - 0.6563 \]
\[ R^2 = 0.9985 \]
Near-wellbore damage

Civan (2001)
Darcy’s Law

\[ u = \frac{qB}{2\pi hr} = \frac{K}{\mu} \frac{dp}{dr} \]
Sulfur solubility in natural gas (Roberts, 1997)

\[ H_2S + S_x \iff H_2S^{(x+1)} \]

\[ c = \rho^4 \exp \left[ -\frac{4,666.}{T} - 4.571 \right] \]
Rate of precipitation

\[
\frac{dV}{dt} = q \left( \frac{dC}{dp} \right)_T dp
\]
Porosity reduction by deposition

Assume perfect packing

\[ \varepsilon = \phi_0 - \phi \]
Permeability reduction by fractional deposit volume

Effective = equilibrium or stationary amount of precipitate considered for correlation of permeability

\[
\frac{K}{K_o} = \exp(-a\varepsilon)
\]
Particle deposition equation

\[ \frac{d\varepsilon}{dt} = \left( \frac{bq^2}{r^2} \right) \exp(a\varepsilon) \]

\[ \varepsilon = 0 \quad , \quad t = 0 \]
Dimensionless Solutions

\[ r_D^2 = \frac{1 - \exp(-a\phi_o)}{1 - \exp(-a\varepsilon)} \exp(-2s) \frac{t_D}{t_D} \]

\[ \frac{K}{K_o} = 1 - \frac{1 - \exp(-a\phi_o)}{r_D^2} \exp(-2s) \frac{t_D}{t_D} \]
Transient-state Deposit Profiles

Civan (2001)

Precipitate Amount, $\varepsilon$

Radial Distance, $\ln r_D$

Copyright 2006 by Faruk Civan
Final Remarks

The formulations provided here can simulate the various damage mechanisms and their effects on formation damage.
Thank you for your attention

☐ Questions?
☐ Discussions?
☐ Comments?