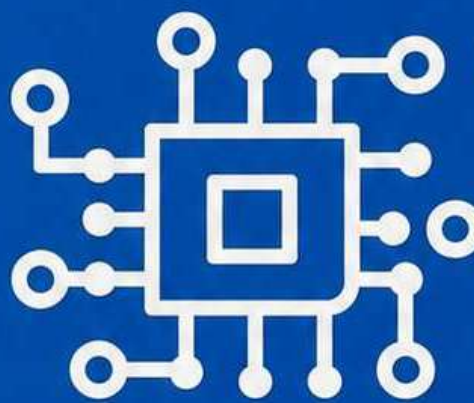




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NUMERICAL MODELING OF TRANSIENT OIL FILTRATION WITH PRESSURE-GRADIENT-SENSITIVE PARTICLE RETENTION IN POROUS MEDIA

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Annotation. This study develops a coupled numerical model for transient oil filtration in porous media with pressure-gradient-sensitive particle retention. Darcy flow, particle transport, deposition, and permeability loss are solved by implicit finite differences and upwinding. Grid and time-step refinement show numerical consistency, while simulations reveal localized clogging and reduced outlet velocity.

Keywords: porous media; transient oil filtration; particle retention; pressure gradient; clogging; permeability impairment; finite-difference method; numerical modeling.

G'OVAK MUHITDA BOSIM GRADIENTIGA SEZGIR ZARRACHALAR USHLANISHI BILAN NEFTNING NOSTATSIONAR FILTRATSIYASINI SONLI MODELLASHTIRISH

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Annotatsiya. Maqolada g'ovak muhitda neftning nostatsionar filtratsiyasi uchun bosim gradientiga sezgir zarrachalar ushlanishini hisobga oluvchi sonli model ishlab chiqildi. Darsi oqimi, zarrachalar ko'chishi, cho'kma to'planishi va o'tkazuvchanlik kamayishi o'zaro bog'landi. To'r va vaqt qadamini maydalash sonli natijalarning izchilligini ko'rsatdi, hisoblashlar esa lokal kolmatatsiya va chiqish tezligi kamayishini ko'rsatdi.

Kalit so'zlar: g'ovak muhit; neft filtratsiyasi; zarrachalarni ushlash; bosim gradienti; kolmatatsiya; o'tkazuvchanlik; chekli ayirmalar usuli; sonli modellashtirish.

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INTRODUCTION

Particle-bearing liquids moving through porous formations can retain fines at grain surfaces and pore constrictions, reducing hydraulic connectivity and permeability. In oil-production and injection problems this coupling may produce localized formation damage. The present study considers one-dimensional, single-phase, slightly compressible oil flow with suspended particles and focuses on how the local hydraulic state influences particle capture.

The aim is to formulate and numerically test a pressure-gradient-sensitive retention law within a compact transient filtration model. The tasks are to couple pressure, particle transport, deposition and permeability loss; construct a stable finite-difference algorithm; verify grid and

time-step sensitivity; and compare the proposed closure with a capacity-limited retention model.

LITERATURE REVIEW AND METHODOLOGY

Numerical and multiscale studies have established that retained particles can reduce pore connectivity and permeability, while recent work has also used machine-learning and CFD-DEM approaches to characterize clogging and impairment [3; Art. 118736], [4; Art. 119272], [5; P. 355–372], [6; P. 831–851], [2; Art. 103408]. These studies confirm the importance of linking particle deposition with hydraulic response.

For oil filtration, models have been developed for heterogeneous media, clay-particle sedimentation, slowly conducting layers, two-phase systems and deep-bed filtration [10; Art. 012018], [8; P. 353–360], [9; P. 511–519], [11; Art. 020004], [7; P. 299–308]. Colloid studies further show that hydrodynamic conditions affect attachment and release [12; P. 9652–9660], [1; P. 12096–12105]. The issue addressed here is a compact retention closure that adapts to the evolving pressure gradient while remaining suitable for repeated engineering calculations.

A saturated one-dimensional layer, $0 < x < L$, is considered. Oil is slightly compressible, single-phase and isothermal; viscosity and porosity are constant. Gravity, hydrodynamic dispersion and particle detachment are neglected. Pressure, mobile-particle concentration and retained-particle concentration are denoted by $p(x, t)$, $c(x, t)$ and $\sigma(x, t)$, respectively.

The superficial filtration velocity follows Darcy's relation:

$$v(x, t) = -\frac{k(\sigma)}{\mu} \frac{\partial p}{\partial x} \quad (1)$$

Slight compressibility gives the pressure-balance equation:

$$\phi c_t \frac{\partial p}{\partial t} = \frac{\partial}{\partial x} \left[\frac{k(\sigma)}{\mu} \frac{\partial p}{\partial x} \right] \quad (2)$$

The mobile and retained particle phases satisfy the conservation relation:

$$\phi \frac{\partial c}{\partial t} + \frac{\partial(v c)}{\partial x} = -\frac{\partial \sigma}{\partial t} \quad (3)$$

Pressure-gradient-sensitive retention closure

The local pressure-gradient magnitude is

$$G(x, t) = \left| \frac{\partial p}{\partial x} \right| \quad (4)$$

The effective retention coefficient is defined by

$$\lambda_{\text{eff}}(x, t) = \lambda_0 \frac{\left(1 - \frac{\sigma}{\sigma_{\text{max}}}\right)^m}{1 + \alpha_G \left(\frac{G}{G_{\text{ref}}}\right)^n} \quad (5)$$

Here λ_0 is the reference retention coefficient, σ_{max} the effective deposition capacity, m and n are exponents, α_G is the gradient-sensitivity parameter, and G_{ref} is the reference pressure gradient. Equation (5) is a phenomenological constitutive hypothesis rather than a universal law; its coefficients require calibration against core-flood or field data. The qualitative role of hydrodynamic forcing is consistent with colloid-retention studies [12; P. 9652–9660], [1; P. 12096–12105].

The retained-particle source term is

$$\frac{\partial \sigma}{\partial t} = \lambda_{\text{eff}}(x, t) |v| c \quad (6)$$

Permeability deteriorates with deposit accumulation according to

$$k(\sigma) = k_0 \exp\left(-\beta \frac{\sigma}{\sigma_{\text{max}}}\right) \quad (7)$$

Normalized permeability is

$$K_r(x, t) = \frac{k(x, t)}{k_0} \quad (8)$$

The feedback is summarized as $p \rightarrow G \rightarrow \lambda_{\text{eff}} \rightarrow \sigma \rightarrow k \rightarrow v \rightarrow c$: pressure redistribution changes capture, deposition changes permeability, and permeability feeds back into flow and particle transport.

Initially, the layer has uniform pressure and contains no mobile or retained particles:

$$p(x, 0) = p_0, \quad c(x, 0) = 0, \quad \sigma(x, 0) = 0 \quad (9)$$

Fixed pressures are imposed at the layer ends, with $p_{\text{in}} > p_{\text{out}}$:

$$p(0, t) = p_{\text{in}}, \quad p(L, t) = p_{\text{out}} \quad (10)$$

Particles enter at the inlet and a zero-gradient concentration condition is imposed at the outlet:

$$c(0, t) = c_{\text{in}}, \quad \frac{\partial c}{\partial x}(L, t) = 0 \quad (11)$$

A uniform mesh $x_i = i\Delta x$, $t^n = n\Delta t$ is used. At each new time level, permeability is reconstructed from the current deposit and interface permeabilities are evaluated by the harmonic mean:

$$k_{i+\frac{1}{2}}^n = \frac{2k_i^n k_{i+1}^n}{k_i^n + k_{i+1}^n} \quad (12)$$

The pressure equation is advanced by the fully implicit approximation

$$\phi c_t \frac{p_i^{n+1} - p_i^n}{\Delta t} = \frac{1}{\mu \Delta x^2} \left[k_{i+\frac{1}{2}}^n (p_{i+1}^{n+1} - p_i^{n+1}) - k_{i-\frac{1}{2}}^n (p_i^{n+1} - p_{i-1}^{n+1}) \right] \quad (13)$$

The resulting tridiagonal system is solved by the Thomas algorithm, after which the interface Darcy velocity is evaluated as

$$v_{i+\frac{1}{2}}^{n+1} = - \frac{k_{i+\frac{1}{2}}^n}{\mu} \frac{p_{i+1}^{n+1} - p_i^{n+1}}{\Delta x} \quad (14)$$

After the pressure update, G_i^{n+1} and λ_{eff} are reconstructed. Advective particle transport is represented by the first-order upwind flux

$$F_{i+\frac{1}{2}}^n = \max(v_{i+\frac{1}{2}}^{n+1}, 0) c_i^n + \min(v_{i+\frac{1}{2}}^{n+1}, 0) c_{i+1}^n \quad (15)$$

The max/min terms select the upstream concentration according to the velocity sign. The mobile concentration is updated by

$$\phi \frac{c_i^{n+1} - c_i^n}{\Delta t} + \frac{F_{i+\frac{1}{2}}^n - F_{i-\frac{1}{2}}^n}{\Delta x} = -R_i^n \quad (16)$$

with deposition sink

$$R_i^n = \lambda_{\text{eff},i}^n |v_i^{n+1}| c_i^n \quad (17)$$

The deposited concentration is then capped by σ_{max} and permeability is recalculated:

$$\sigma_i^{n+1} = \min[\sigma_{\text{max}}, \sigma_i^n + \Delta t R_i^n] \quad (18)$$

$$k_i^{n+1} = k_0 \exp\left(-\beta \frac{\sigma_i^{n+1}}{\sigma_{\text{max}}}\right) \quad (19)$$

This staggered procedure retains the two-way coupling between hydraulic state, capture, transport and permeability without solving a large fully coupled nonlinear system.

At each time step the MATLAB program reconstructs k from σ , forms harmonic interface permeabilities, solves the implicit pressure system, evaluates Darcy velocities and G , computes λ_{eff} , builds upwind particle fluxes, updates c and σ , refreshes k , and stores outlet velocity, minimum k/k_0 , maximum σ and $\lambda_{\text{eff}}/\lambda_0$. The implementation is compatible with MATLAB 7.5.0 (R2007b).

The computational domain has length $L=10$ m and is simulated for 30 days. The reference gradient is $G_{\text{ref}} = (p_{\text{in}} - p_{\text{out}})/L=5.0 \times 10^5$ Pa/m. The baseline closure uses $\alpha_G=0.50$ and $n=m=1.0$; the remaining physical and numerical parameters are listed in Table 1.

The closure parameters are exploratory settings selected for a controlled numerical experiment and are not calibrated reservoir constants.

Table 1.**Physical and numerical parameters used in the simulations.**

Parameter	Symbol	Value
Formation length	L	10 m
Porosity	φ	0.20
Total compressibility	c_t	$1.0 \times 10^{-9} \text{ Pa}^{-1}$
Initial permeability	k_0	$1.0 \times 10^{-14} \text{ m}^2$
Oil viscosity	μ	$5.0 \times 10^{-3} \text{ Pa}\cdot\text{s}$
Inlet pressure	p_{in}	15 MPa
Outlet pressure	p_{out}	10 MPa
Inlet particle concentration	c_{in}	0.01
Maximum retained concentration	σ_{max}	0.08
Permeability sensitivity	β	2.5
Gradient sensitivity	α_G	0.50
Gradient exponent / capacity exponent	n / m	1.0 / 1.0
Spatial and time steps	$\Delta x / \Delta t$	0.10 m / 600 s
Simulation time	T	30 days

Four reference retention coefficients are examined: $\lambda_0=0, 0.5, 1.0$ and 2.0 m^{-1} . The $\lambda_0=0$ case provides the non-clogging hydraulic reference; $\lambda_0=1.0 \text{ m}^{-1}$ is used as the baseline for detailed analysis.

Spatial refinement was performed with $\Delta t = 600$ s and temporal refinement with $\Delta x = 0.10$ m. The day-30 outlet velocity and minimum normalized permeability are compared in Table 2.

Table 2.**Grid and time-step sensitivity of the baseline solution.**

Study	$\Delta x, \text{ m}$	$\Delta t, \text{ s}$	$v_{\text{out}}, \text{ m/day}$	$\min(k/k_0)$
Spatial	0.20	600	0.079885	0.641692
Spatial	0.10	600	0.080066	0.642139
Spatial	0.05	600	0.080156	0.642394
Temporal	0.10	1200	0.080067	0.642116

Study	Δx , m	Δt , s	v_{out} , m/day	$\min(k/k_0)$
Temporal	0.10	600	0.080066	0.642139
Temporal	0.10	300	0.080065	0.642154

DISCUSSION

Reducing Δx from 0.10 to 0.05 m changes the outlet velocity by 0.113% and $\min(k/k_0)$ by 0.040%. Reducing Δt from 600 to 300 s changes the same outputs by 0.00094% and 0.0022%. These variations are much smaller than the model-to-model effects considered below.

RESULTS

For $\lambda_0 = 1.0 \text{ m}^{-1}$, the damaged zone remains concentrated near the inlet. The minimum k/k_0 decreases from 0.9820 on day 1 to 0.9164 on day 5, 0.8450 on day 10 and 0.6421 on day 30, corresponding to a maximum local permeability loss of 35.79% (Figure 1).

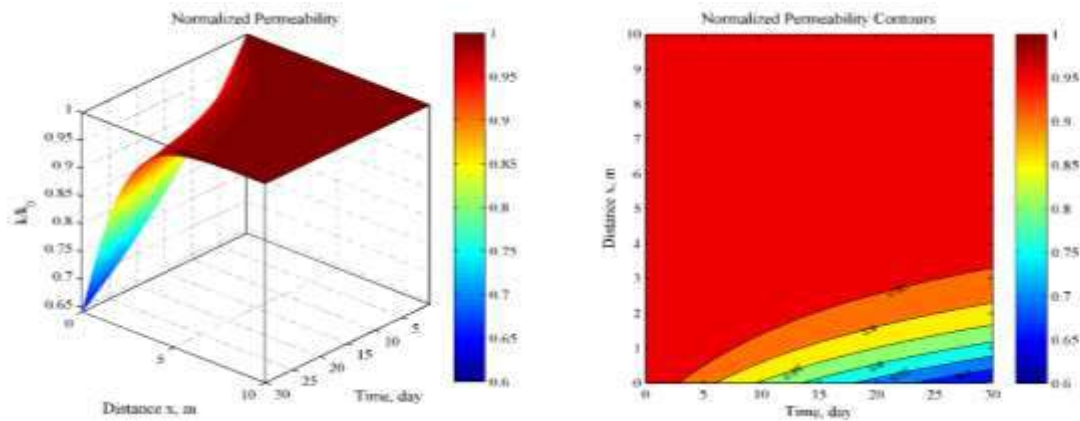


Figure 1. Spatial-temporal evolution of normalized permeability.

The retained-particle field is strongly nonuniform. At day 30, $\sigma \approx 0.00798$ at $x=1$ m and 0.00414 at $x=2$ m, but falls to 4.52×10^{-4} at $x=5$ m and 3.99×10^{-5} at $x=8$ m. The corresponding k/k_0 values are 0.7794, 0.8786, 0.9860 and 0.9988.

Because both deposition capacity and G/G_{ref} evolve, λ_{eff}/λ_0 is spatially and temporally variable. Its minimum decreases from 0.6584 on day 1 to 0.4804 on day 30; at day 30 it is about 0.565 at $x=1$ m and 0.683 at $x=8$ m (Figure 2).

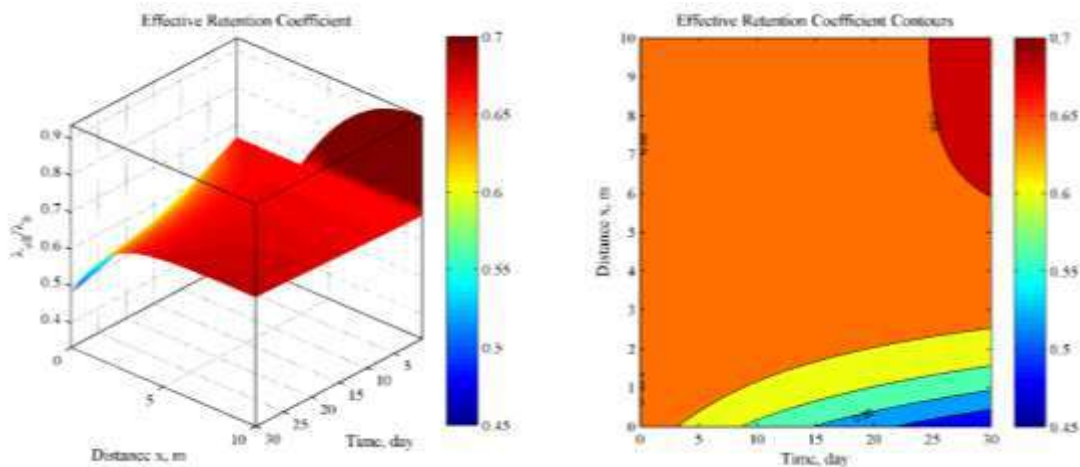


Figure 2. Spatial-temporal evolution of the effective retention ratio λ_{eff}/λ_0 .

Increasing λ_0 strengthens deposition and reduces hydraulic capacity. At day 30 the outlet-velocity loss relative to $\lambda_0=0$ is 6.07%, 7.33% and 8.64% for $\lambda_0=0.5, 1.0$ and 2.0 m^{-1} , while the corresponding minima of k/k_0 are 0.7850, 0.6421 and 0.4678.

For $\lambda_0=1.0 \text{ m}^{-1}$, setting $\alpha_G=0$ gives $\min(k/k_0)=0.5116$ and an 8.22% outlet-velocity loss. With $\alpha_G=0.5$ these values become 0.6421 and 7.33%. Thus, gradient sensitivity reduces the estimated maximum local permeability loss by about 13.05 percentage points, whereas the global velocity reduction changes by only 0.89 percentage points.

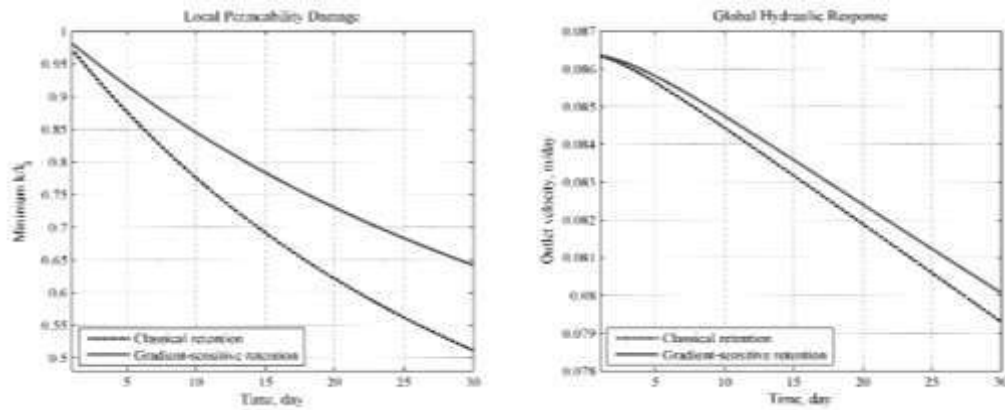


Figure 3. Local permeability damage and global hydraulic response for the two retention models.

The results show a scale effect: a localized upstream clogging zone strongly changes the minimum permeability but only modestly alters outlet flow. The evolving λ_{eff} field is controlled by hydraulic forcing and remaining deposition capacity. Because the coefficients are exploratory, reservoir use requires calibration and extension to detachment, dispersion, heterogeneity and multiphase effects.

CONCLUSION

The calculations confirm that pressure-gradient-sensitive retention materially changes the predicted local formation damage. For $\lambda_0=1.0 \text{ m}^{-1}$ and $\alpha_G=0.5$, $\min(k/k_0)=0.6421$ and the day-30 outlet-velocity loss is 7.33%. Increasing λ_0 from 0.5 to 2.0 m^{-1} raises the velocity loss from 6.07% to 8.64%. Relative to the capacity-limited model, the proposed closure reduces the maximum local permeability-loss estimate by about 13.05 percentage points. Spatial and temporal refinements change the principal outputs by less than 0.12% and 0.003%, respectively.

Further work should calibrate λ_0 , α_G , n , m , β and σ_{max} against core-flood or field data and extend the model to heterogeneous multidimensional, dispersive and multiphase conditions.

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