Numerical investigation on the impact of particle density and flow velocity on particle transport and deposition in a randomly oriented fracture

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Abstract:

Introduction/purpose: Fractured formations recently gained significant interest as a landscape for securing both energy and groundwater demands, However, the dual role of fracture in transporting fluids and contaminants underscores the need for further investigations to mitigate the impact on human health. This study aims to numerically investigate the combined effect of particle density and flow velocity on their transport and deposition in different fracture orientations.

Methods: A 2D particle tracing simulation was implemented accounting for drag and gravity forces on a smooth fracture. The derived particle numbers under the studied scenario e.g., fracture orientation, particle density, and flow velocity, were fitted to a 1D advection-dispersion equation with a deposition term.

Results: The model elucidated that both particle densities yielded an increase in the normalized concentration in non-horizontal scenarios as the fracture orientation angle increased. The overall increment led to an observed decrease in the deposition coefficients and was associated with an increase in the dispersion coefficients. Hence the effect was more pronounced for denser particles where gravitational settling dominated, particularly in horizontal fractures. Less dense particles (1.05 g/cm³) were more strongly influenced by hydrodynamic forces, exhibiting lower overall *deposition and dispersion across all fracture orientations. Additionally, increased flow velocity enhanced mechanical mixing and amplified dispersion and deposition coefficients.*

Conclusion: The findings demonstrated a clear dependency on the combined effect of fracture orientation, particle density, and flow velocity. These valuable insights into particle transport mechanisms in fractured media have applications in subsurface flow, contaminant migration, and reservoir engineering.

Keywords: fractured media, particle density, inclination angle, flow velocity, dispersion, deposition.

Introduction

The evolving global landscape is increasingly characterized by escalating energy and water requirements, which have led to the depletion of hydrocarbon reserves and the deterioration of groundwater quality. Recently, porous fractured formations have emerged as crucial resources to meet future water demands and ensure sustainable long-term energy supply (Qu et al, 2021). The development of fractured rock reservoirs necessitates a balanced approach, as it has the potential to significantly impact surrounding groundwater systems and, by extension, human health. Groundwater contamination, particularly in areas dependent on fractured aquifers, poses a serious threat. Studies reveal that approximately 5% of annual deaths, among 820,000 individuals are attributed to compromised groundwater quality, particularly affecting children under the age of 5 (Lin et al, 2022). Such alarming statistics highlight the urgent need to improve our understanding of groundwater flow and contaminant migration in fractured media.

The term fracture is a general description of geological discontinuities including joints, faults, and cracks (Chrysikopoulos & Syngouna, 2014), that results when mechanical shear or normal stress reaches a certain extent. Naturel fractures occupy a small portion with respect to the entire volume of the hosting rock and encounter a variety of surfaces and expanding directions based on their origin formation. For example, tectonic fractures are characterized by complex rough wall surfaces and random orientation associated with the local tectonic events (Baiyu et al, 2021), while regional fractures exhibit fewer orientation changes along their length (Tiab & Donaldson, 2016). Meanwhile, local apertures of the natural fracture tend to vary spatially following a normal or lognormal distribution (Chrysikopoulos & James, 2003; Stoll et al, 2019), adding more complexities to fluids and particle transport phenomena. However, the fluid velocity across these apertures remains orders of magnitude higher than that in the matrix (Zvikelsky & Weisbrod, 2006) serving fractures as primary channels and contributing to increasing the permeability of the rock (James & Chrysikopoulos, 2003).

In association with mechanical rupture processes or as a result of internal micro-erosion, solid particles can filtrate from the vadose zone towards the fractured reservoirs with a size distribution that could reach 10 μm (Zhang et al, 2012) and their origin can significantly define their charge and density. The cumulative studies have also justified that larger particles are inhibited from diffusing into the matrix and travel faster compared to solutes in single fractures due to charge, size exclusion, or the combined effect (Stoll et al, 2019; Spanik et al, 2021). Dense large particles are subject to gravity settling and demonstrated as a major mechanism accounting for particle deposition and retention in horizontally oriented fracture (Ding et al, 2021).

Numerical and experimental studies have been dedicated to examining the physical factors influencing the behavior of particles and solutes during their transport in fractured media such as dense particles in a uniform aperture (Bagalkot & Kumar, 2018; James & Chrysikopoulos, 1999), flow velocity variation effect (Medici et al, 2019; Mondal & Sleep, 2012), aperture distribution (Stoll et al, 2019; Ding et al, 2021) and the consideration of fracture surface roughness (Baiyu et al, 2021; Wang et al, 2020). Hence, the aforementioned body of literature treats the settling effect perpendicularly to the flow direction as fractures are oriented horizontally. Theoretically considering, the gravity effect is dependent on the inclination angles of the sample, which could promote or retard the transport mechanism. In porous media, the dispersion coefficient is highly susceptible to the inclination angle of the packed column as discussed by Chrysikopoulos & Syngouna (2014); hence the orientation of the fractures affected the recovered dense polydisperse particles where vertically oriented fractures which exhibited faster transport compared to diagonals and horizontals (Ding et al, 2021). Despite these valuable insights, a critical research gap remains in understanding the specific effects of particle density on transport and retention in non-horizontal fractures. While the behavior of dense particles in vertical fractures has been explored to some extent, there is a limited understanding of how varying particle densities influence transport in fractures that are not horizontally aligned. Non-horizontal fractures, including those with diagonal or complex inclinations, introduce additional complexities to particle transport, such as altered flow velocities, shear forces, and gravitational impacts that may interact differently with particles of varying densities.

The current study aims to numerically investigate the effect of fracture orientation on the transport and retention of solid particles and tends to compare the impact of particle density and flow velocity on the overall implemented scenarios. First, a 2D particle tracing simulation is constructed on a rough matched wall fracture using COMSOL Multiphysics software.

The simulation accounts for upward and downward flow on different fracture inclination angles, and the injected particles at the fracture inlet were characterized with 2.6 g/cm^3 and 1.05 g/cm^3 densities. Moreover, the breakthrough curves, representing the recovered particles at the outlet, were analyzed and fitted using a one-dimensional advection-dispersion equation that incorporates a deposition term to derive the transport parameters.

This approach enables a more comprehensive understanding of particle transport dynamics under varying the aforementioned physical conditions.

Methodology

The current study employed a numerical simulation approach following the combination of finite elements methods (FEMs) and the Lagrangian particle tracking (LPT) method on a two-dimensional confined single fracture using COMSOL Multiphysics. The following constructed model aims to investigate the interactions between fluid flow and solid particles considering realistic conditions of particles motion within different fracture orientations. The following sections provide a detailed breakdown of the simulation setup, the governing equations, the boundary conditions, and the solver configuration.

Physical system

To examine the particle transport behavior in fractured media while considering the effect of fracture surface roughness, fracture orientation, particle density, and flow velocity, a sinusoidal fracture is constructed in this study (Natarajan & Kumar, 2010) and the elevation points ($\mathrm{y_i}$) along the length of the fracture are obtained as follows:

$$y_i = sin(x_i) - sin\left(\frac{x_i}{4}\right) \times sin(3x_i) \qquad (1)$$

where x_i is the coordinates of points (100 points with a separation distance of 1 mm) along the x direction as depicted in Figure1.

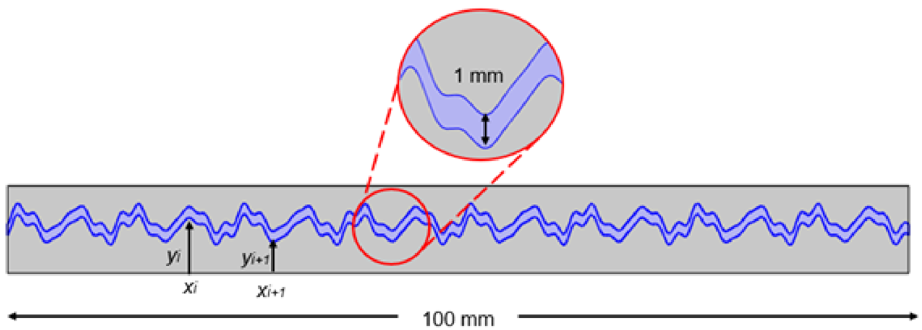

Figure 1 – Geometrical configuration of the sinusoidal fracture

A fine mesh with non-uniform size was constructed to optimize the accuracy in the areas where the particle-wall interactions and the flow gradient were significant. Ten layers of a finer mesh near the fracture walls were constructed to capture the parabolic flow velocity and particle positions. The mesh element size ranged from 0.0125 and 0.0286 mm. A mesh independence study was conducted to ensure that further refinement had a negligible impact on the results, with the final mesh containing 22865 domain elements and 2425 boundary elements.

Governing equations

Particle transport in a 2D saturated fracture with different inclinations was modeled using a particle tracing module implemented in COMSOL Multiphysics. (COMSOL Inc., Stockholm, Sweden). The fracture is 100 mm in length with 1 mm of aperture (Figure1). Particle transport occurs following the local parabolic velocity profile along the x direction at different fracture orientations. A simplified scheme of the general system model in this study is illustrated in Figure 2.

This study considers that particles are transported under a laminar regime. The fluid motion is governed using Navier's-Stokes equation (Baiyu et al, 2021) as follows:

$$\rho \frac{\partial U}{\partial t} + \rho (U.\nabla)U = \nabla.(-pI + K) + F_{ex} \quad (2)$$

$$\rho\nabla. U = 0 \quad (3)$$

where ρ and U are the fluid density (M.L-3) and velocity (L.T-1), ∇ p is the pressure gradient and F_{ex} denotes the volume external force term (M.L.T-2), K the liquid stress tensor (ML-1T-2), and I is the identity matrix.

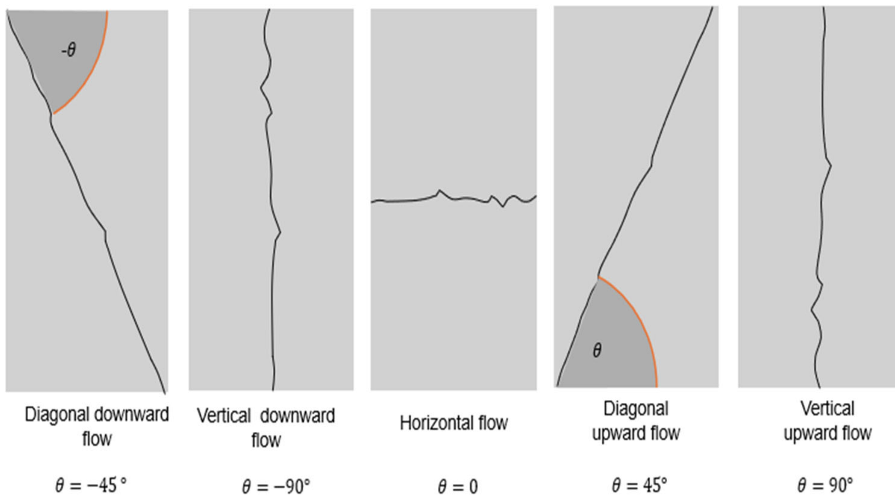

Figure 2 – Different fracture inclinations scenarios

The particle tracing method employed in this study models particles as discrete entities that move through a fluid, interacting with their environment under the influence of various external forces. This approach allows for a detailed examination of particle behavior within the flow field. This study assumes particle transport is governed primarily by advection, without considering other transport mechanisms such as diffusion. As a result of this assumption, the forces acting on the particles are simplified to include only drag and gravity.

Gravitational force exerts an influence on the particle and acts perpendicular to the flow direction. According to Bennacer et al. (2017) and Bennacer et al. (2023), the gravity force is expressed as:

$$F_g = \frac{4}{3}\pi\, d_p^3(\rho_p - \rho).g \tag{4}$$

The drag force on a spherical particle is determined by Stokes' law (Guha Roy & Singh, 2016):

$$F_d = \frac{1}{\tau_p} m_p(U - U_p) \tag{5}$$

Here m_p and U_p are the particle mass (M), and velocity (L.T^{-1}) respectively, d_p is the particle diameter (L) ρ_p is the particle density (M.L^{-3}), g is the acceleration of gravity, and τ_p Is the relaxation time (T) given by Stokes drag law (Kim & Zydney, 2004) as:

$$\tau_p = \frac{\rho_p\, d_p^2}{18} \tag{6}$$

The particle trajectories and positions as a function of time are determined by Newton's second law and force balance acting on particles (Belfort & Nagata, 1985):

$$m_p \frac{d\, U_p}{dt} = F_g + F_d \tag{7}$$

Particle generation and boundary condition

During this simulation, in order to explore the effect of gravity, the particles are assumed to be spherical and monodisperse with a uniform size of 1 µm and a density of 2.6 g/cm^3 and 1.05 g/cm^3. An N_0 number consisting of 100,000 particles is released as a short pulse for 30 seconds with a random distribution at the inlet of the fracture. Moreover, the interaction of particles with the walls of the domain was governed by freeze boundary conditions as follows:

$$v = v_c \tag{8}$$

where v is the vertical component of the particle velocity, and v_c is the particle velocity when striking the wall.

Freeze condition was used to mimic favorable conditions for particle attachment with the fracture surface. The particle's vertical position no longer changes after establishing contact with the fracture wall.

This study assumes no flow between the fracture and the matrix (no matrix diffusion). A no-slip condition was implemented for the boundaries, and the laminar flow is controlled from the inlet at two average flow velocities of 0.02 and 0.03 cm/s while the outlet boundary condition was set to a constant pressure p_0 of 0 Pa, allowing for continuous fluid flow through the domain.

$$[-pI + K]n = p_0 n \tag{9}$$

An implicit time-stepping scheme was used to solve time-dependent studies of the governing equation regarding particle trajectory and fluid flow through the confined geometry. This approach allows suitable transient dynamics capturing and ensuring numerical stability. A sensitivity analysis was conducted to ensure further reduction of time step did not affect simulation results. Furthermore, 0.001s was set as a fixed time step throughout the simulation.

The governing equations of the studied system were solved according to the Multifrontal Massively Parallel Sparse Direct (MUMPS) Solver. The solver is well-suited for 2D systems and all scale problems with complex boundary conditions. To maintain the model accuracy, 1E-6 was set as a strict convergence tolerance. The solver's strict tolerance ensured that residuals in the governing equations were minimized, leading to reliable convergence.

Advection dispersion equation

The relationship describing the one-dimensional transport of particles in a saturated fracture with no matrix diffusion considering advection, dispersion, and deposition term (Abdel-Salam & Chrysikopoulos, 1994) is:

$$\frac{\partial C}{\partial t} + K_{dep}C = D_L\frac{\partial^2 C}{\partial x^2} - U_p\frac{\partial C}{\partial x} \tag{10}$$

where C is the effluent concentration of particles (M/L^3), x is the distance along the fracture from the inlet (L), t is the time, U_p is the particle velocity (L/T), D_L is the hydrodynamic longitudinal dispersion coefficient (L.T^{-2}) and K_{dep} is the kinetic deposition coefficient (T^{-1}).

A short pulse is mathematically considered as an instantaneous injection (Bennacer et al, 2022). The following initial and boundary conditions are applied:

$$C(x,0) = 0 \tag{11}$$

$$C_{(x=0,t)} = \begin{cases} C_0\,, 0 \leq t \leq t_{inj} \\ 0\,, \qquad t > t_{inj} \end{cases} \tag{12}$$

$$\frac{\partial C}{\partial x}_{(x=L,t)} = 0 \tag{13}$$

An analytical solution for Eq.(7), at the fracture outlet ($x = L$), for an instantaneous injection at the fracture inlet is given in Eq.(9) (Bodin et al, 2003; Yosri et al, 2021):

$$C(L,t) = \frac{M_0 L}{Q\sqrt{4\pi D_L t^3}} \exp\left[-\frac{\left(L - U_p t\right)^2}{4\, D_L t}\right] \exp\left[K_{dep} t\right] \tag{14}$$

In order to fit the obtained result from the particle tracing module to the analytic solution, the cumulative particle number at the outlet for each scenario is expressed as concentrations with the initial particle concentration obtained as follows (Zvikelsky et al, 2008):

$$C = \frac{\rho_p\, N_0\, \pi d^3}{6\, V_{inj}} \tag{15}$$

where N_0 is the initial particle number released at the inlet and V_{inj} is the injected particle suspension volume. In this study, the V_{inj} is considered as 3 fracture volumes ($3FV$) where $FV = L.W.b$

Table 1 – Simulation parameters

	Value	Unit
Injected particle number	1000 000	
Particle diameter (monodisperse)	1	µm
Particle density	2600 1050	kg/m^3
Water density	1000	kg/m^3
Water viscosity	0.001	Pa.s
Water inlet velocity	0.02 0.03	cm/s

Results and discussion

Particle transport behavior under the effect of fracture orientation

Based on the particle tracing methodology outlined earlier, this study has expanded to simulate distinct scenarios, each characterized by variations in fracture orientation. The scenarios explore different combinations of flow velocity and particle density. The transport parameters are determined by fitting the obtained result from the particle tracing simulation breakthrough curves (BTCs) to the analytical solution of Eq. (9). Figure 3 shows the BTCs at different fracture orientations under the tested flow velocities and particle densities.

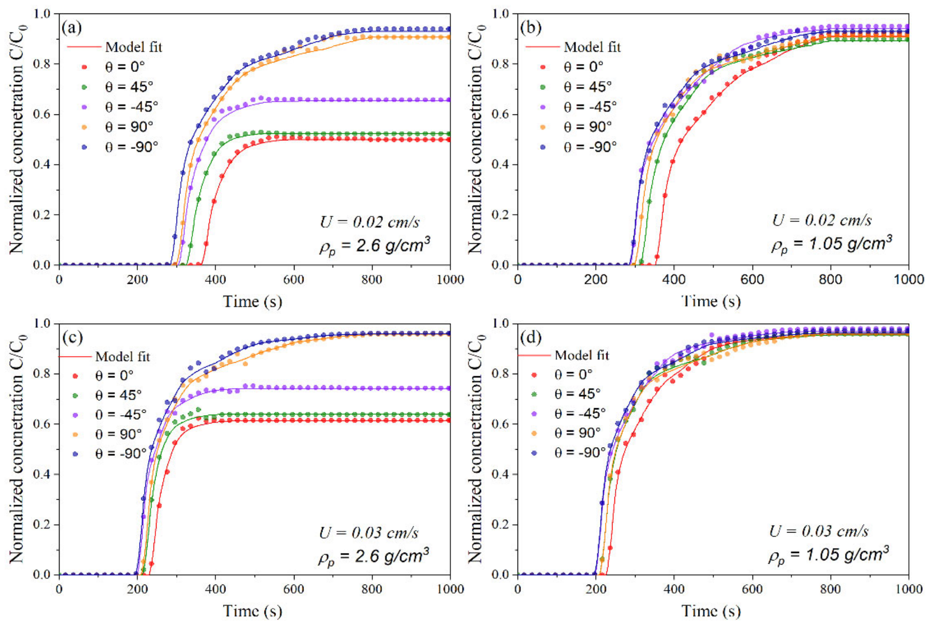

Figure 3 – BTCs of the injected particles (a), (b) $U = 0.02\ cm/s$ (c), (d) $U = 0.03\ cm/s$ for $\rho_p = 2.6\ g/cm^3$ and $\rho_p = 1.05\ g/cm^3$

The observation from Figure 3 demonstrates a strong correlation between the analytic solution and the derived results of particle tracing simulations, which underscores the reliability of the developed model in accurately depicting particle transport mechanisms. Across the tested flow velocities and particle densities, the earliest breakthrough occurs when the inclination angle θ = ±90°, indicating the least retardation of particles in both upward and downward flow conditions. The slight reduction in the normalized concentration observed at +90° is attributed primarily to the influence of gravity, as particles moving upward experience greater gravitational resistance unlike those moving downward. Similar results were found by Ding et al. (2021).

In non-vertical configurations, the transport of dense particles exhibited distinct behaviors. At a flow velocity of U = 0.02 cm/s, the normalized concentration reached 0.65 for an inclination of -45° and 0.52 for +45° (Figure 3 (a),(c)). When the flow velocity increased to U = 0.03 cm/s, the normalized concentration at these angles increased to approximately 0.74 and 0.63, respectively, as depicted in Figure 3 (b),(d). Notably, these inclined conditions exhibited higher concentration plateaus compared to the horizontal fractures, indicating greater particle retention within the fracture under horizontal flow conditions, Figure 4(a).

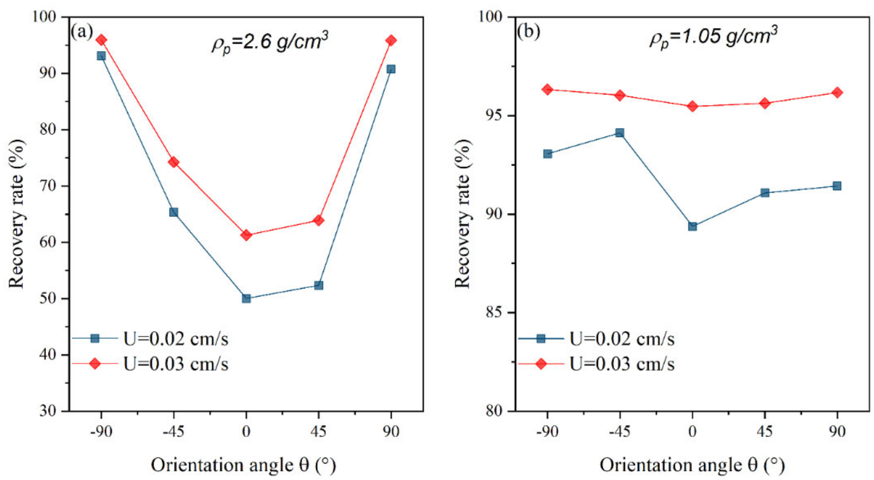

Figure 4 – Recovery rates for (a) $\rho_p = 2.6\ g/cm^3$ and (b) $\rho_p = 1.05\ g/cm^3$.

For particles with a density of 1.05 g/cm³, the effect of orientation on transport dynamics was less pronounced. In both upward and downward non-horizontal flow scenarios, these particles experienced similar breakthrough curves, characterized by an increased relative concentration and the establishment of a plateau after 800 seconds at U = 0.02 cm/s and 650 seconds at U = 0.03 cm/s (Figure 3). Unlike the behavior of dense particles, where gravity plays a substantial role, the transport of these lighter particles is governed primarily by buoyancy forces maintaining the particles within the central streamlines, resulting in rapid transport through the fracture and higher recovery rates as depicted in Figure 4(b).

Additionally, the flow velocity was found to have a significant influence on particle transport across all scenarios. Higher flow velocities consistently led to faster breakthroughs and higher recovery rates. The enhanced advective forces reduce the residence time of a particle and help to overcome the retardation caused by gravitational settling or particle-wall interactions, allowing for faster movement through the fracture.

Hydrodynamic dispersion coefficient

The effect of fracture orientation, particle density, and flow velocity on the dispersion coefficient is illustrated in Figure 5. As it is clear, the orientation had a significant effect on the dispersion process and was more pronounced for dense particles. At 0° all particles have the minimum dispersion coefficient, hence as the fracture orientation deviates from horizontal, the dispersion increases to reach the highest values for downward flow conditions. The modeled fracture in the current study is rough to a certain extent due to sinusoidal undulation and at nonhorizontal fracture orientation, the flow and the settling effect led to a more lateral spread of particles and increased the likelihood of wall-particle interaction compared to 0° fracture orientation. This behavior leads to an increase in the dispersion coefficient. Hence at downward flow, the gravitational force acts as a positive driver that amplifies particle velocity which yields the highest dispersion coefficient.

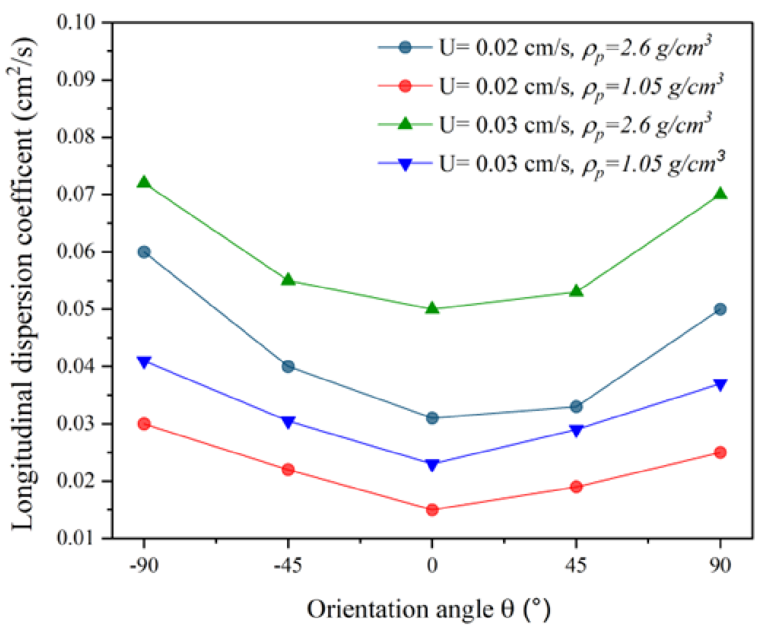

Figure 5 – Hydrodynamic longitudinal dispersion coefficient as a function of the fracture inclination angle

The effect of orientation was significant; however, the density also played a major role. Dense particles exhibited higher dispersion coefficients compared to those with 1.05 g/cm3. This can be attributed to the settling effect wherein denser particles experience a greater degree of gravitational pull. As these particles settle, their vertical movement is impeded, leading to a lateral shift towards the lower surface of the fracture which in turn increases particle-wall interactions, thereby enhancing dispersion. In contrast, less dense particles tend to remain within the streamline, where the flow velocity is at its maximum. These particles experience less residence time in the system, resulting in fewer particle-surface collisions and, consequently, lower dispersion coefficients.

Higher flow velocities lead to an increase in dispersion coefficient under all the fracture orientations and particle densities. Similar results were reported by Mondal & Sleep (2012) and Hawi et al. (2023). The behavior has been attributed to the mechanical mixing and the formation of vortices near the rough fracture walls. These vortices promote more chaotic particle motion, increasing the likelihood of particles interacting with the fracture surfaces, which further amplifies particle dispersion, particularly in fractures with non-horizontal orientations.

Deposition coefficient

Figure 6 illustrates the variation in the kinetic deposition coefficient K_{dep} as a function of fracture orientation angles under given flow velocities and particle densities. The results demonstrate a clear dependency of deposition kinetics on the fracture inclination angle, with horizontal fractures (0°) exhibiting the highest deposition coefficient across all tested scenarios, and it is significant for denser particles. The observation is consistent with the low particle recovery rates observed in the horizontal fracture, as previously shown in Figure 4(a). As the fracture orientation increases from horizontal to more inclined positions, the deposition coefficient decreases for all conditions, indicating that fracture geometry significantly influences particle settling and deposition dynamics.

Dense particles encounter a pronounced deposition process where the horizontal fracture seems an ideal configuration for particle settling. At horizontal inclination gravity acts perpendicularly to the flow direction and causes a significant reduction in the vertical component of particle velocity, delaying the particle's overall migration through the fracture. This deceleration increases the likelihood of particle-wall interactions, as particles are pulled toward the stagnation zones located near the fracture surfaces where the flow velocity approaches zero.

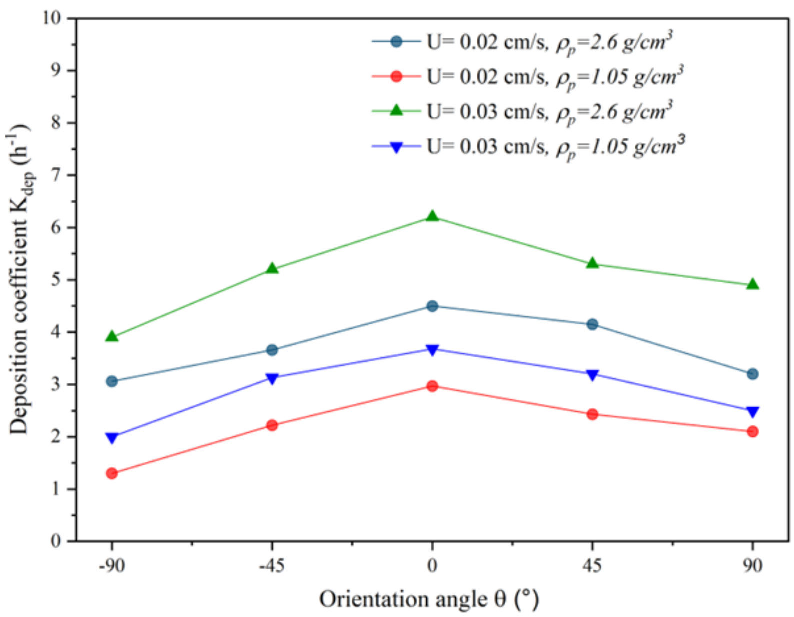

Figure 6 – Deposition coefficient versus the fracture inclination angle

The role of gravity becomes even more complex when considering inclined fractures; hence it plays a positive role in downward flow accelerating particle velocity and is characterized by a lower deposition coefficient compared to upward flow conditions. Less dense particles, though following a similar trend, exhibit lower deposition coefficients compared to their denser counterparts. In this case, the primary mechanism driving deposition is not gravitational settling but rather the interaction of particles with trapping zones within the fracture geometry. These trapping zones of low flow velocity are caused by the undulations in the modeled fracture surface. The trapped particles in these regions experience minimum transport forces but significant shear stress leading to re-entrainment towards the centerline where the velocity is maximal and exhibits a lower deposition coefficient than that of dense particles under similar conditions.

As the flow velocity increases, the deposition coefficient rises across all tested fracture inclination angles and particle densities. Similar trends of increased deposition with rising flow velocity have been observed in porous media studies, as discussed by Bennacer et al. (2013) and in the recent work (Bennacer et al, 2022). The author attributed the behavior to the increased mechanical mixing generated at higher flow velocities where particles are more likely to establish enhanced particle-wall interactions.

Conclusion

A numerical approach has been developed and applied to simulate the impact of particle density and flow velocity of monodispersed particles transported in a randomly orientated rough fracture. A particle tracing simulation is implemented to track particle movement in a laminar flow determined by Navier's Stocks equation within a sinusoidal 2D fracture. Moreover, a 1D advection-dispersion equation is employed to quantify and analyze the transport parameters. The study revealed that fracture orientation plays a critical role in governing particle transport, dispersion, and deposition. As the orientation angle increases, the normalized concentration increases and is higher in downflow scenarios, e.g. -45 and -90.

Moreover, there is a marked decrease in the deposition coefficient and a corresponding increase in the dispersion coefficient for particles of both densities. However, this effect is notably more pronounced for denser particles (2.6 g/cm^3) due to sedimentation emerging as the primary deposition mechanism, particularly in horizontal fractures. In this configuration, gravity acts perpendicularly to the flow, decelerating particle velocity and promoting deposition by increasing particle-wall interactions and trapping particles in stagnation zones. This gravitational deceleration leads to enhanced retention of denser particles in horizontal fractures.

In contrast, less dense particles (1.05 g/cm^3) are more strongly governed by hydrodynamic forces rather than gravitational settling. This results in reduced overall deposition and dispersion for these particles across all fracture orientations, with their behavior being more influenced by flow dynamics than by orientation-specific effects.

Irrespective of the studied density, particles experience greater drag force as flow velocity increases, which in turn enhances their contact with the fracture surface. This results in an increase in both the dispersion and deposition coefficients. The improved mechanical mixing disrupts the flow streamlines, promoting particle interactions with the rough fracture walls and amplifying particle spreading and retention within the fracture. This effect is more significant for denser particles due to their greater susceptibility to gravitational settling. Still, less dense particles also exhibit increased dispersion and deposition at higher flow velocities, driven by enhanced drag force.

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Investigación numérica sobre el impacto de la densidad de partículas y la velocidad del flujo en el transporte y deposición de partículas en una fractura orientada aleatoriamente

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CAMPO: ciencias de computación, mecánica
TIPO DE ARTÍCULO: artículo científico original

Resumen:

Introducción/propósito: Las formaciones fracturadas ganaron recientemente un interés significativo como paisaje para asegurar las demandas de energía y agua subterránea. Sin embargo, el doble papel de la fractura en el transporte de fluidos y contaminantes subraya la necesidad de realizar más investigaciones para mitigar el impacto en la salud humana. Este estudio tiene como objetivo investigar numéricamente el efecto combinado de la densidad de las partículas y la velocidad del flujo en su transporte y deposición en diferentes orientaciones de fractura.

Métodos: Se implementó una simulación de seguimiento de partículas en 2D que tiene en cuenta las fuerzas de arrastre y gravedad en una fractura lisa. Los números de partículas derivados en el escenario estudiado, por ejemplo, orientación de fractura, densidad de partículas y velocidad de flujo, se ajustaron a una ecuación de advección-dispersión 1D con un término de deposición.

Resultados: El modelo aclaró que ambas densidades de partículas produjeron un aumento en la concentración normalizada en escenarios no horizontales a medida que aumentaba el ángulo de orientación de la fractura. El incremento general condujo a una disminución observada en los coeficientes de deposición y se asoció con un aumento en los coeficientes de dispersión. Por lo tanto, el efecto fue más pronunciado para las partículas más densas donde dominaba la sedimentación gravitacional, particularmente en las fracturas horizontales. Las partículas menos densas (1,05 g/cm^3) se vieron más influenciadas por las fuerzas hidrodinámicas, exhibiendo una menor deposición y dispersión general en todas las orientaciones de fractura. Además, el aumento de la velocidad del flujo mejoró la mezcla mecánica y amplificó los coeficientes de dispersión y deposición.

Conclusión: Los hallazgos demostraron una clara dependencia del efecto combinado de la orientación de la fractura, la densidad de las partículas y la velocidad del flujo. Estos valiosos conocimientos sobre los mecanismos de transporte de partículas en medios fracturados tienen aplicaciones en el flujo subterráneo, la migración de contaminantes y la ingeniería de yacimientos.

Palabras clave: medios fracturados, densidad de partículas, ángulo de inclinación, velocidad de flujo, dispersión, deposición.

Численное исследование влияния плотности частиц и скорости потока на перенос частиц и осаждение в случайно ориентированной трещине

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РУБРИКА ГРНТИ: 27.35.30 Математические модели механики частиц и систем
ВИД СТАТЬИ: оригинальная научная статья

Резюме:

Введение/цель: В последнее время значительно возрастает интерес к трещиноватым пластам в силу потребности в энергии и подземных водах. Однако двойная роль, которую трещины играют в распределении жидкостей и загрязнений, указывает на необходимость в дальнейших исследованиях для минимизации воздействия на здоровье человека. Целью данной статьи является численное исследование совместного влияния плотности частиц и скорости потока на их перенос и осаждение в трещинах различной пространственной ориентации.

Методы: Применено 2D-моделирование движения частиц с учетом сил сопротивления и притяжения к гладкой трещине. Затем численные результаты частиц, полученные в этом сценарии, т.е. ориентация трещины, плотность частиц и скорость потока, были введены в одномерное уравнение адвекции и дисперсии с выражением осаждения.

Результаты: Модель показала, что обе плотности частиц приводят к увеличению нормализованной концентрации в негоризонтальных сценариях с увеличением угла ориентации трещины. Общее увеличение привело к наблюдаемому снижению коэффициентов осаждения, что связано с увеличением коэффициентов дисперсии. Вследствие чего эффект был более выраженным у более плотных частиц, у которых преобладало гравитационное осаждение, особенно в горизонтальных трещинах. Выявлено, что частицы с меньшей плотностью (1,05 г/см^3) в большей степени подвержены влиянию гидродинамических сил, что приводит к снижению общего осаждения и дисперсии во всех направлениях трещин. Кроме *того, увеличение скорости потока улучшает механическое перемешивание и увеличивает коэффициенты дисперсии и осаждения.*

Вывод: Полученные данные показали прямую зависимость от совместного влияния ориентации трещины, плотности частиц и скорости потока. Эти ценные сведения о механизмах переноса частиц в трещиноватых средах находят применение в подземном течении, миграции загрязняющих веществ и разработке коллекторов.

Ключевые слова: трещиноватая среда, плотность частиц, угол наклона, скорость потока, диспергирование, осаждение.

Нумеричко истраживање утицаја густине честица и брзине струјања на транспорт и депозицију честица у присуству произвољно оријентисаног лома

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Сажетак:

Увод/циљ: Однедавно је знатно повећан интерес за формације са ломом у оквиру задовољавања потреба за енергијом и подземним водама. Међутим, двострука улога коју има лом у транспорту течности и контаминаната скреће пажњу на неопходност даљих истраживања како би се умањио утицај на здравље људи. Циљ ове студије јесте да нумеричким путем испита комбиновани утицај густине честица и брзине струјања на њихов транспорт и депоновање у присуству ломова различитих оријентација.

Методе: Примењена је 2Д симулација кретања честица при чему су узете у обзир сила отпора и гравитације на глатком лому. Затим су нумерички резултати честица добијени у том сценарију, тј. оријентација лома, густина честица и брзина струјања, унети у 1Д једначину адвекције и дисперзије са изразом за депозицију.

Резултати: Модел је показао да су, како се угао оријентације лома повећавао, обе густине честица довеле до повећања нормализоване концентрације у нехоризонталним случајевима. Укупан прираст је довео до уоченог смањивања коефицијената депозиције и повезан је са повећањем коефицијената дисперзије.

Стога је ефекат био израженији у случају гушћих честица где је доминирало гравитационо окружење, нарочито код хоризонталних ломова. Честице мање густине (1,05 g/cm³) биле су под јачим утицајем хидродинамичких сила, па су показале слабију укупну депозицију и дисперзију код свих оријентација лома. При томе је повећана брзина струјања побољшала механичко мешање и повећала коефицијенте дисперзије и депозиције.

Закључак: Налази показују јасну зависност од комбинованих ефеката оријентације лома, густине честица и брзине струјања. Ови значајни увиди у механизам транспорта честица у срединама с присуством лома имају примену у подземним токовима, редукцији контаминације и конструисању резервоара.

Кључне речи: средине са ломом, густина честица, угао нагиба, брзина струјања, дисперзија, депозиција.

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