

Review of Particle Detachment and Attachment in Porous Media

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Abstract

Particle detachment, migration and attachment are common processes in porous media, especially in unconsolidated formations. In this review, the processes are discussed and equations describing the processes are presented. Two particle detachment processes analyzed are the hydrodynamic forces and electric double-layer forces. The particle detachments equations were critically examined to determine if they reflect crucial factors that trigger particle detachment in porous media. Essential factors that are missing in the equation are the effect of pressure and the level of rock consolidation. Incorporating the level of rock cementation and the effect of pressure in the equations will make the models more empirical and less theoretical. For particle attachment, Van der Waals forces, adhesion, particle attachment efficiency and straining processes and their equations are considered. The colloidal forces are all embraced in terms of capturing important elements that mobilize particles in porous media, however, the practical application of the models can pose a challenge. For particle adsorption on grain surfaces, it is recommended that the effect of pressure and temperature be studied.

Keywords: *Hydrodynamic, Colloid, Forces, Equation, Straining.*

1. Introduction

Particle attachment, detachment and migration are common phenomena in porous media that are of interest in the petroleum industry. This is because some reservoir formations are unconsolidated and as such continuously generate sand and clayey particles during production which creates a number of problems. Understanding particle mobilization in formations and the trigger factors is important since this is fundamental to modelling the process. Factors that trigger particle dislodgment and migration in porous media have been studied and effort has been made to capture some of them in equations for particle detachment and attachment in reservoir rocks. This paper reviews particle detachment and attachment processes in porous media and equations that describe the processes.

Porous media can be defined as solid bodies with a network of voids from pore spaces between solid particles which vary in size and shape. Porous media includes the vadose (unsaturated) and phreatic (saturated) zones of the formation. Particles in porous media can get detached from parent rocks, start the migration and can eventually get attached to grain surfaces depending on interaction processes prevalent in the system and between particle and rock surfaces. Particle transport in porous

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media follow the path of fluid flow as the particle is suspended in the flow and this is called advection. Other particle transport mechanisms include interception, Brownian motion and gravity settling.

1.1. Particle Mobilization Factors in Porous Media

The unconsolidated state of a formation does not imply that particles must mobilize; some factors initiate particle detachment from the rock matrix and promote mobilization. These factors have been investigated and reported by several authors [1, 2]. The effect of a high flow rate on particle mobilization has been discussed [3, 4, 5] and it has been reported that high pressures can counter the effect of a high flow rate in mobilizing formation particles, hence high formation pressure can militate against particle detachment [6]. The effects of water production and water salinity on clay particle mobilization have been studied and it is observed that as salinity decreases, the tendency for particle detachment increases and vice versa [7, 8, 9]. In all of these, however, it should be noted that the level of rock consolidation is very crucial in determining if rock particles will detach or not. Consolidated formations are not prone to particle detachment like unconsolidated formations, hence the level of rock cementation needs to be considered.

Other factors that trigger particle detachment in porous media include formation wettability, high temperature, high viscosity fluids, formation weakness and fatigue [1, 10, 11]. Most times these factors work together in combination to mobilize particles during fluid flow, although one or more factors could be dominant depending on the existing conditions in the system. Part of the objective of this review is to determine how factors that influence particle mobilization in porous media are reflected in particle detachment and attachment equations. For the sake of emphasis, these factors are production rate or velocity of fluid flow, pressure, temperature, water salinity, wettability, type of fluid in terms of viscosity and level of rock cementation or consolidation.

There are different types of particles that detach from and attach to coarse sand grains in porous media during fluid flow. These include microorganisms, fine sand particles, organic matter, inorganic matter, minerals and clays. In this study, however, the focus is on very fine sand particles and the migratory clay, kaolinite. Clays are mainly affected by colloidal forces [12] while sand particles are mostly affected by hydrodynamic forces [13]. In any case, both colloidal and hydrodynamic forces influence particle detachment and attachment in porous media to some extent thus, both forces are considered. Mechanisms for very small particle attachment and detachment such as colloids include electric double-layer forces, London van der Waals forces, gravity settling and straining. Primary mechanisms for large particle attachment and detachment such as large sizes of sand grains include straining, gravity settling and hydrodynamic forces.

1.2 Colloidal Forces of Particle Detachment and Attachment

Formation particles are usually transported by fluid through a distance before they are deposited on an immobile surface in porous media. Colloidal particle transportation in an entrained fluid is dominated by Brownian diffusion and after deposition on a surface, attachment is influenced by several other forces. The theory of these forces propounded by Derjaguin, Landau, Verwey and Overbeek which describes particle stability and the interplay of forces between charges when two particles approach each other is termed the DLVO theory [12]. The interaction energies described by the DLVO theory partially dominate particle attachment of colloids and are used to predict colloid particle attachment on solid surfaces. DLVO force is a sum total of the electric double layer, Van der Waals attraction and Born repulsion energies as expressed in the following equations:

$$V_T = V_{EDL} + V_{VW} + V_{BR}$$

Where,

V_T = Total DLVO energy
 V_{EDL} = Electric Double layer energy
 V_{VW} = Van der Waals energy
 V_{BR} = Born repulsion energy

The electric double-layer energy is dependent on charges of the colloid and grain surfaces which may be positive or negative; similar forces result in repulsion while opposite forces result in attraction. The Van der Waals energy arises from the attraction between two close surfaces. The Born repulsion arises from short-range repulsive forces in electron clouds overlapping around atoms. Paths of a colloid surface interaction due to Van der Waals forces, Born repulsion and the electric double layer which are dominant in the classical DLVO theory are presented in Figure 1.

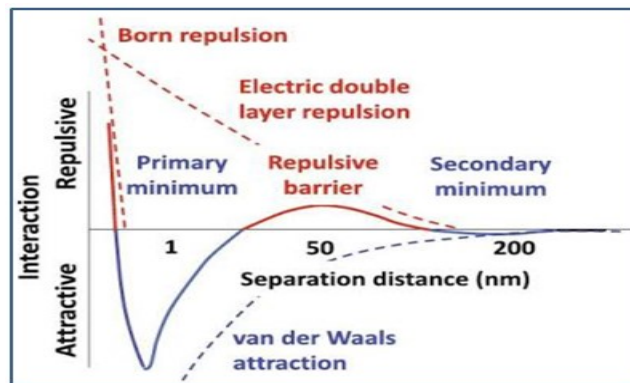


Figure 1: The Classical DLVO Theory on Interaction Energy for Particle Dispersion

One flaw with the DLVO theory is that it assumes all surfaces to be homogeneous (monolithic) which is not an ideal representation of the average interaction energy of colloids. It does not account for micro-scale to nano-scale heterogeneity that exists on real surfaces, hence it overgeneralizes the surface characteristics of colloids and collectors [14]. It is therefore necessary to incorporate heterogeneity into colloid collector surface DLVO interactions.

2. Forces Responsible for Particles Detachment in Porous Media

One of the most important particles detaching forces is the hydrodynamic forces which comprise the drag and lift forces. When particle detaching forces are stronger than the attaching forces, particles are mobilized along with the flow. The detachment rate is therefore partly dependent on the drag forces prevalent in the system [15]. Nevertheless, a consolidated rock can tolerate high flow forces and still keep its formation particles intact which is not possible in unconsolidated rocks, making production rate a critical factor in particle mobilization. Detached and mobilized colloidal particles which are suspended in fluids exhibit random movements termed Brownian motion. The magnitude of this motion increases with decreasing particle size [16]. Two primary forces that detach formation particles from the rock matrix are hydrodynamic force and colloidal forces. Examination of these forces will indicate if factors that mobilize fine particles in porous media are reflected in the force equations.

2.1 Hydrodynamic Force of Particle Detachment

The hydrodynamic force that detaches dense particles from the rock matrix is mainly controlled by the velocity or rate of fluid flow through porous media. Goren and Spielman [17, 18] explained fine particle detachment from sand grain surfaces due to uniform shear flow using Eq.1 given as:

$$F_{SHM} = 6\pi\mu a_p^2 (3A_s U \sin\theta_p / 2a_s)(H+1)F(H) \quad (1)$$

Where

F_{SHM} = Hydrodynamic force that detaches fine particles from rock matrices or the surface of sand grains.

$$H = h/a_p \quad (2)$$

H = Separation distance between the fine particles and the sand grain surface (assumed to be 20\AA).

a_p = Radius of the fine particle

h = Distance between the particles in the formation is given as 20\AA [19].

μ = Viscosity of the fluid

A_s = Porosity

U = Velocity of the fluid

θ_p = Angle between the radial coordinate of the centre of the fine particle and the direction of flow

a_s = Radius of the sand grain

$F(H)$ = Universal hydrodynamic function of the dimensionless gap

The hydrodynamic equation presented in Equations 1 and 2 is fundamental in describing particle detachment from porous media. Two hydrodynamic factors that pull particles away from their parent rocks are fluid viscosity and flow velocity and these are considered in the hydrodynamic equation presented. Fluid viscosity can sometimes indicate fluid type and fluid carrying capacity while fluid velocity is the drag force and a dominant and critical factor that is often tied to economics in the oil and gas industry. But these are not the only factors; others that play important roles but are not captured in Equations 1 and 2 are pore pressure, overburden pressure and the level of rock cementation. Al-Awad [6] pointed out that at high confining pressures, high flow rates can be achieved without sand production. This implies that high formation pressures can counter the effects of high flow rates and as such needs to be reflected in the hydrodynamic force equation for particle detachment in porous media. Cementation which is a very influential element in determining the strength of a rock needs to be expressed in the equation but is missing. Hence, there is a need for modification of the hydrodynamic equation for particle detachment in porous media especially in petroleum reservoir rocks where fluid flow is critical to production and are sometimes altered. The dimensionless universal hydrodynamic function of Eq. 1 can be modified to reflect these properties.

2.2 Colloidal Forces that Detach Particles from Porous Media

The stability of particles in solution is affected by the total energy of interaction when these particles are close to each other. This total energy of interaction includes the electric double layer repulsion (DL), Born repulsion, Van der Waals (VW) and hydrodynamic forces [20, 21]. These colloidal forces consider factors such as temperature, ionic strength, zeta potential and other constant parameters. Born repulsion is disregarded because it is assumed that the distance of interaction between particles and pore surface is more than 1nm. For very low flow rates (such as 1ml/min), hydrodynamic forces are also disregarded. Therefore, the two primary dominating colloidal forces (F_T) are the double layer repulsive forces (F_{DL}) and Van der Waals attractive forces (F_{vw}). A combination of these two forces are expressed as:

$$F_T = F_{DL} + F_{vw} \quad (3)$$

The electric double layer repulsive force and Van der Waals force promote particle detachment and attachment respectively. Summation of the electric double layer force and Van der Waals force determines the total colloidal force operating in a porous medium of which the stronger force dominates either to promote particle attachment or detachment. The electric double layer equations are presented below while the Van der Waals forces and equations are discussed under particle attachment processes.

2.2.1 The Electric Double Layer Force

The double layer repulsive force is strongly dependent on electrolyte concentration and the pH of the fluid [22]. There are several model equations for the double layer repulsive force and one of them is given as:

$$F_{DL} = 2\pi a_p (nKT/\kappa) \cdot \{(y_1^2 + y_2^2)(1 - 1/\tanh(kh)) + 2y_1 y_2 / \sinh(kh)\} \quad (4)$$

Where

a_p = Radius of fine particles

n = Number of ions per unit volume

K = Boltzmann's constant

T = Temperature

κ = Debye-Huckel reciprocal length parameter

y_2 = Reduced surface potential of the fine particles

y_1 = Reduced surface potential of sand grains

$$y_1 = ze\psi_i / KT$$

(5)

Where,

z = Valence of the counter ions

e = Electron charge

ψ_i = Surface Potential

$$\kappa^2 = 2e^2 n z^2 / \epsilon KT \quad (6)$$

Where,

ϵ = Permittivity of the fluid medium

Another model for double layer repulsive forces is given as:

$$V_{DLR} = (\epsilon a_p / 4) \{ 2\zeta_{01}\zeta_{02} \ln[(1 + \text{Exp}(-kh))/(1 - \text{Exp}(-kh))] + (\zeta_{01}^2 - \zeta_{02}^2) \ln[1 - \text{Exp}(-2kh)] \} \quad (7)$$

Where,

V_{DLR} = electric double layer repulsion energy

ϵ = Dielectric constant

k = Debye length

h = Distance between the two particles

ζ_{01} = Zeta potential of one of the two kinds of particles involved in the interaction
 ζ_{02} = Zeta potential of the other kind of particles

The values of the constant parameters used in Eq. (7) are given in Table 1. The Debye length (k) and Hamaker constant (A_H) have been derived and given [22-24] but determining these parameters for specific cases can pose a challenge because they are not easy to obtain.

Table 1: Values of some constant parameters used in Eq. 7

Constants	Value
Dielectric constant (ϵ)	6.94257×10^{-12}
Particle radius (a_p)	$1.3 \times 10^{-5}m$
Debye Length (k)	$(9.6 \times 10^{-9})^{-1}m$
Hamaker constant (A_H)	6×10^{-21}
Boltzmann constant (K_B)	1.38×10^{-23}
Temperature	297K

In vadose and phreatic environments, the typical condition is that both colloids and collector surfaces carry negative charges which result in electric double-layer repulsion. This leads to unfavorable conditions for attachment but favors the detachment of particles from the rock matrix. On the other hand, the presence of certain positively charged particles in porous media results in attractions, depositions and attachments. In any case, the electric double-layer force plays a key role in determining colloidal particle detachment and attachment energies in porous media, provided such flows are lamina and hydrodynamic forces are negligible.

The colloidal forces presented in Eq. (4), (5), (6) and (7) through complex, tend to embrace all the factors that affect colloid particle detachment in porous media. This includes temperature, ionic properties which covers water salinity, and probably wettability is taken care of under hydrophobicity properties. However, the practical application of these equations to produce usable data or figures is a challenge because determining some of the parameters in the equations such as the distance between two particles, the radius of fine particles and Debye length is not easy to obtain.

3. Forces Responsible for Particles Attachment in Porous Media

Attachment is the removal of colloids from the solution, depositing and fixating them to the solid phase. It can also be defined as the mobilization of particles through physical contact of the colloid onto the collector surface within the primary energy level. The attachment of colloids on surfaces depends on colloid-colloid, colloid-solvent and colloid-porous media interactions. For small particles in porous media, mechanisms of colloid contact to collector include interception, inertia impaction, sedimentation, electrostatic forces, adsorption and straining [16]. In this section of the review, the colloidal forces of Van der Waals are considered along with adsorption, particle attachment efficiency and attachment by straining.

3.1 Colloidal Forces that Attach Particles to Porous Media

Van der Waals forces are colloidal forces of attraction that play vital roles in the process of particle attachment in porous media. It is a weak force compared to chemical bonding and ionic forces but is an important intermolecular force described as a combination of forces between induced and permanent dipoles. The Van der Waals forces consist of the London dispersion forces between instantaneous induced dipoles, Debye forces between permanent dipoles and induced dipoles, and Keesom force between permanent dipoles. The London Van der Waals are the weakest intermolecular force due to the formation of temporary dipoles but they are present in all molecules.

3.1.1 Van der Waals Equations

Van der Waals force plays a major role in supporting the attachment of fines to pore surfaces [21]. According to Gregory [25], the Van der Waals force between a fine particle and a sand grain is given as:

$$F_{vw} = -2\pi a_p (A/12\pi h^2) \{1/[(5.32h/\lambda) + 1]\} \quad (8)$$

Where,

λ = London wave length which is approximately 100nm [25].

A = Hamaker constant given as 1.7×10^{-20} J [26].

h = Distance between the two particles

a_p = Radius of the fine particles

With respect to the assumptions of spheres or plate geometry [24], the force as a result of London Van Waals is given as:

$$V_{LVA} = (-A_H/6) \left[\frac{2}{H} \left(1 + \frac{H}{H} \right) \left(2 + \frac{H}{H} \right) + \ln \left(\frac{H}{2} + \frac{H}{H} \right) \right] \quad (9)$$

Where,

V_{LVA} = London Van der Waals energy

H = Distance of separation

A_H = Hamaker constant

Note that in Eq. (9), London wave length and the size of the particles (in terms of diameter) are neglected while attention is given to the separation distance between the two surfaces considered.

3.2 Particle Adsorption in Porous Media

Adsorption is another particle attachment mechanism in porous media which involves the adhesion of substances to a surface. It is the attachment of particles to a solid due to attractive forces between colloids and surfaces. Adsorption is a surface phenomenon where a film of the adsorbate is created on the surface of the adsorbent due to physicochemical interactions. There are two types of adsorption; physical adsorption called physisorption and chemical adsorption called chemisorption. Physical adsorption involves Van der Waals forces which are weak and reversible. Chemical adsorption involves chemical bond formation which is stronger and irreversible and is not common in porous media during fluid flow but is responsible for rock cementation.

Eba [27] reported that clay can eliminate Manganese II (Mn II) from aqueous solutions through the process of adsorption. The adsorbate is the material or substance being adsorbed which in this case is Mn (II) while the adsorbent is the adsorbing material which in this case is clay. The equation is given as follows:

$$q_t = (C_0 - C_t)V/m \quad (10)$$

Where

q_t = The amount of Mn (II) ions adsorbed per unit mass of adsorbent (dimensionless)

V = Volume of Manganese solution.

m = Mass of clay

C_o = Initial Mn (II) concentration.

C_t = Mn (II) concentration at any time contact of interaction between the adsorbate and adsorbent.

In using Eq. (10) to describe the trapping and adsorption of clays to other particles, the adsorbate becomes the clay while the adsorbent is any other type of particles (eg sand grains) under consideration. The parameters are thus re-defined as follows:

q_t = The amount of clay adsorbed per unit mass of adsorbent (sand grains)

V = Volume of clay particles in solution.

m = Mass of any other particles under consideration

C_o = Initial clay concentration.

C_t = Clay concentration at any time contact of interaction between the adsorbate and adsorbent.

Eq. (10) is over simplified because it is only accounting for the mass of colloids deposited on surfaces without giving attention to the forces that are responsible for such depositions. It does not also indicate the type of adsorption process, whether physisorption or chemisorption. One major challenge in using this model is how to experimentally quantify the amount of clays adsorbed on the sand grain surfaces so that the amount can be compared against model results. However an interesting area to explore in adhesion is the study of pressure and temperature effects on particle attachment in porous media. Models of the process can be derived and scaled up to describe the effect of temperature and pressure on particle attachment in petroleum reservoir systems.

3.3 Particle Attachment Equations

One model for particle attachment in porous media consists of the attachment efficiency equations. Particle attachment (η) is a product of attachment efficiency (α) and collector efficiency (η_o) which is expressed as:

$$\eta = \alpha\eta_o \quad (11)$$

The term α stands for the chemical interaction between the particles and porous media, and the term η_o is defined as the ratio of the rate at which particles strike the porous media (collector) to the rate at which the particles flow towards the collector which accounts for physical interactions.

3.3.1 Particle Attachment Efficiency

The Particle efficiency model has tried to describe particle attachment in porous media by treating it as an empirical parameter that captures all aspects of particle deposition not described by the more extensively validated particle transport model [28]. The attachment efficiency (α) is a function of several phenomena which include Van der Waals forces, electric double layer interactions, hydration forces and particle surface hydrophobicity. Attachment efficiency is unity when there are no barriers to deposition and attachment is favored, but exceeds unity (one) if phenomena at small distances attract particles to its surface. Based on the observations of particles behavior in porous media and under a couple of assumptions, an equation to estimate this attachment efficiency (α) has been derived and is expressed as:

$$\alpha = [-2d/3(1 - \epsilon)\eta_o L] \ln(C/C_o) \quad (12)$$

Where

C/C_o = Concentration factor of effluent particle remaining
 α = Attachment efficiency factor
 C = Particle concentration present at distance L
 C_o = Particle concentration present at $L = 0$
 d = Diameter of a collector which is assumed to be spherical
 η_o = Clean bed single collector efficiency
 L = Length of Porous media
 ε = Porosity of the medium

3.3.2 Collector Efficiency

The single collector efficiency of suspended particles transport around a spherical collector is defined as the sum of the contact efficiencies due to three mechanisms. These mechanisms are contributions due to particle diffusion onto a solid surface, interception of particle deposition trajectory and particle deposition due to gravity and Van der Waals attraction. The single collector contact efficiency (η_o) is therefore expressed as:

$$\eta_o = \eta_D + \eta_I + \eta_G \quad (13)$$

Where

η_D = Contact efficiency due to diffusion
 η_I = Contact efficiency due to interception
 η_G = Contact efficiency due to gravitational force

The concepts of single collector efficiency and derivation of accompanying equations have been extensively discussed [29]. The single collector coefficient has been expressed as a function of several dimensionless groups given as:

$$\eta_o = 2.4A_s^{1/3} N_R^{-0.081} N_{pe}^{-0.715} N_{vdW}^{0.052} + 0.55A_s N_R^{1.675} N_A^{0.125} + 0.22N_R^{-0.24} N_G^{1.11} N_{vdW}^{0.053} \quad (14)$$

Where

N_R = Aspect ratio of particle size to collector size expressed as
 N_{pe} = Peclet number characterizing ratio of advective transport to diffuse transport
 N_G = Gravitational number
 A_s = Porosity dependent parameter characterizing the structure of the porous medium
 N_A = Attraction number representing the combined influence of van der Waals attraction and fluid velocity on nanoparticle deposition due to interception.
 N_{vdW} = Van der Waals number characterizing the ratio of Van der Waals attraction energy to particle's thermal energy.

$$N_R = d_p/d_c \quad (15)$$

$$N_{pe} = ud_c/\theta D_N \quad (16)$$

$$N_A = A_h/K_B T \quad (17)$$

$$N_G = \frac{[2\alpha_p^2(\rho_p - \rho_f)g\theta]}{9\mu u} \quad (18)$$

$$A_s = [2(1 - Y^3)] / (2 - 3Y + 3Y^5 - 2Y^6) \quad (19)$$

$$Y = (1 - \theta)^{1/3} \quad (20)$$

Where

θ = Porosity
 d_p = Suspended particle diameter

a_p = Radius of the suspended diameter
 u = Darcy velocity of the dispersed particle suspension
 d_c = Collector diameter
 K_B = Boltzmann constant
 T = Temperature
 D_N = Particle diffusion coefficient in an infinite medium
 A_h = Hamaker constant
 ρ_p = Particle density
 ρ_f = Fluid density
 g = Gravitational constant
 μ = Dispersion viscosity

The work done in developing Eq. (11) to Eq. (20) is quite commendable because the equations are all embracing, taking into consideration all the colloidal forces. But the mechanistic single-collector models have been observed to over predict η for Brownian particle transport experiments in favorable conditions. However, the modified model that incorporated the grain to grain contact and low flow parameters produced better agreements with experimental results.

3.4 Colloid Attachment Coefficient in Porous Media

According to Bradford et al 2004, colloid interaction in porous media that results in particle attachment and detachment can be described using the following equation:

$$\begin{aligned}
 \frac{\partial(\rho_b S_{att})}{\partial t} &= \theta_w k_{att} \varphi_{att} C - \rho_b k_{det} S_{att} \\
 \frac{\partial(\rho_b S_{att})}{\partial t} &= \theta_w k_{att} \varphi_{att} C - \rho_b k_{det} S_{att}
 \end{aligned} \tag{21}$$

For a clean bed condition, φ_{att} is equal to 1, reducing the equation to:

$$\frac{\partial(\rho_b S_{att})}{\partial t} = \theta_w k_{att} C - \rho_b k_{det} S_{att} \tag{22}$$

Where

t = Time
 ρ_b = Bulk density
 C = Colloid concentration
 θ_w = Volumetric water content
 S_{att} = Solid phase concentration of attached colloids
 K_{att} = First order colloid attachment coefficient
 K_{det} = First order colloid detachment coefficient

The colloid attachment coefficient is dependent on diffusion, colloid concentration, fluid velocity, gravity and adsorption capacity [30]. The attachment coefficient K_{att} is given as:

$$k_{att} = \frac{3(1-\theta_w)}{2d_{50}} \eta \propto v \tag{23}$$

Where

η = Collector efficiency of the porous medium

α = Colloid sticking efficiency
 θ_w = Volumetric water content
 D_{50} = Grain diameter of the porous media in the median range
 V = Velocity of flow
 η is given as:

$$\eta = 4A_s^{1/3} N_{pe}^{-2/3} + A_s N_{Lo}^{1/8} N_R^{15/8} + 0.00338 A_s N_G^{1.2} N_R^{-0.4} \quad (24)$$

The parameters involved in determining collector efficiency η have been defined in section 3.3.2, but note that the coefficients of the parameters are not the same.

3.5 Attachment by Straining

Experimental analysis have indicated that straining is an important mechanism of colloid retention especially for large colloid particles in a porous medium with small pore throats [15]. Some discrepancies between colloid transport data and attachment theory can be traced to the fact that attachment theory does not account for straining. The straining model is principally interested in determining the amount of particles captured and retained along pore throats.

Straining is the trapping of particles along pore throats that are too small to allow particle passage. The magnitude of colloid retention by straining depends on both colloid and porous medium properties such as size of the particle and size of the pore throat. Figure 2 shows the mechanism of particle trapping (also called straining) in a flow stream along a pore throat with a smaller diameter than the diameter of the migrating particle contained in the stream.

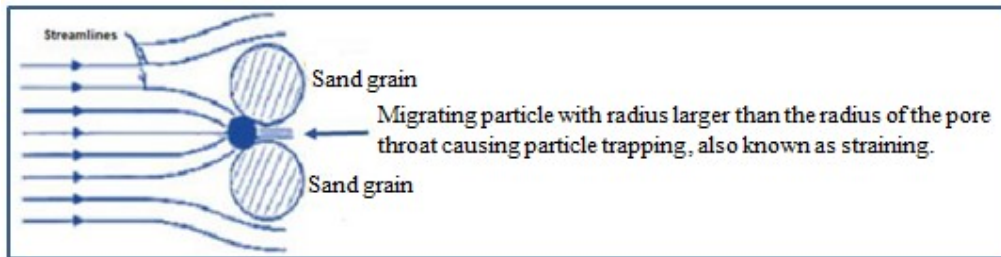


Figure 2: Trapping of a Migrating Particle along a Pore Throat

The modified model for straining by Bradford is given as:

$$\frac{\partial(\rho_b S_{str})}{\partial t} = \theta_w k_{str} \varphi_{str} C \quad (25)$$

Where

K_{str} = Straining coefficient

φ_{str} = A dimensionless straining attachment function for colloids.

S_{str} = Solid phase concentration of strained colloids

θ_w = Volumetric water content

ρ_b = Bulk density

C = Colloid concentration

t = Time

The dimensionless straining function for colloids φ_{str} is given as:

$$\varphi_{str} = H(z - z_0) \left(\frac{d_{50} + z - z_0}{d_{50}} \right)^{-k} \quad (26)$$

Where

β = Colloid shape parameter for spatial distribution

$H(z - z_0)$ = Heaviside function

z = Depth

z_0 = Depth of the column inlet

4. Conclusions

The following are the conclusions made from this review:

1. Processes and mathematical models for hydrodynamic and colloidal forces for particle detachment and attachment in porous media have been presented, discussed and examined.
2. The two colloidal forces considered in particle detachment and attachment in porous media are the double layer repulsive force and Van der Waals attractive forces; the equations are all-embracing in terms of capturing essential elements that affect particle mobilization, but they are cumbersome, making practical application difficult.
3. The hydrodynamic equations for particle detachment capture some crucial factors that promote particle detachment in porous media but do not reflect the effect of pressure and level of rock consolidation.
4. It is recommended that the dimensionless universal hydrodynamic function in the particle detachment equation be modified to capture the effect of formation pressure and rock cementation in the equation.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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