Effect of pH on initiation of fines migration: DLVO modeling and experimental validation

by

ELMIRA DALABAYEVA

THESIS SUPERVISOR

PEYMAN POURAFSHARY

THESIS CO-SUPERVISOR

RIZWAN MUNEER

Thesis submitted to the School of Mining and Geosciences of Nazarbayev
University in Partial Fulfillment of the Requirements for the Degree of
Master of Science in Petroleum Engineering

Nazarbayev University
April 2025

ORIGINALITY STATEMENT

I, Elmira Dalabayeva, hereby declare that this submission is my own work and to the best of my knowledge it contains no materials previously published or written by another person, or substantial proportions of material which have been accepted for the award of any other degree or diploma at Nazarbayev University or any other educational institution, except where due acknowledgement is made in the thesis.

Any contribution made to the research by others, with whom I have worked at NU or elsewhere is explicitly acknowledged in the thesis.

I also declare that the intellectual content of this thesis is the product of my own work, except to the extent that assistance from others in the project's design and conception or in style, presentation, and linguistic expression is acknowledged.

Signed on April 2025

Dal

ABSTRACT

The interaction of rock and fluid elements during production starts formation damage, which reduces permeability and decreases hydrocarbon extraction. In sandstone reservoirs, small solid particles called fine particles start to release and move during the invasion of different fluids during production or oil recovery related operations. This process is called fines migration, a type of formation damage in sandstone reservoirs. Fines migration can affect oil production. Since fines were released and started to migrate through the reservoir, they blocked some of the open holes, which may complicate the fluid flow in porous media and reduce the permeability.

Several factors affect the fines migration initiation. To reduce the fines migration impact on formation damage, parameters such as pH, flow rate, and ionic strength were analyzed to predict at which conditions fines start to move in a sand-fine-brine system. For this purpose, terms such as critical pH and critical flow rate are defined. Critical pH shows at which pH level migration starts, whereas critical flow rate shows the lowest flow rate at which migration does not occur.

Enhanced oil recovery methods, such as injection of low-salinity water and alkaline flooding, alter the salinity and pH inside the formation, which affects the electrostatic interaction forces between fines and the rock surface. There are also hydrodynamic forces that impact the release of the fines. Hence, to predict the fines migration initiation, all these forces should be considered and analyzed. In this work, a modified method based on DLVO (Derjaguin, Landau, Verwey, and Overbeek) theory was used to predict the critical pH to release the fines. Analysis of repulsive and attractive forces resulted in the prediction of critical pH in different conditions. The model predicts that the initiation of fines migration occurs as a function of pH and salinity and predicts critical pH values of 8 and 10 (for 0.2 M NaCl and 0.25 M NaCl, respectively). Furthermore, the model was validated, where critical flow rates at a pH of 8 and a 0.25 M NaCl concentration can be predicted, with a calculated error of 13%. Several coreflooding experiments were conducted to verify our developed model and methodology. Hence, the verified model considered electrostatic, gravitational, and hydrodynamic forces that affect fines migration.

To conclude, DLVO modeling is one of the ways to predict parameters that affect the fines release and further migration by calculating the forces that are influencing the sand-fine-rock system. This method may reduce the experimental work typically necessary for designing operations such as EOR.

ACKNOWLEDGMENT

I extend my sincerest appreciation to Professor Peyman Pourafshary for his unwavering support and invaluable guidance, which kept me motivated throughout this research project. The valuable input, along with specific recommendations, guided the development of this project through his advice. His extensive support, consisting of reviewing my progress and providing advice, and navigating challenges through his time and his dedication, remains deeply valued by me.

The groupmates who work with me are my thanksgiving because they extend both support and knowledge-sharing with professional encouragement. Collaborating with my peers has improved my knowledge base as well as cultivated team-based learning and knowledge exchange among us. We have achieved valuable progress through our team discussions and problem-solving sessions that optimized the research direction. Their double support in academic tasks as well as personal encouragement has transformed this journey into something wholesome since I value the great team environment we built.

I want to express my deepest gratitude to Mr. Reeza Khoramian, who provided technical assistance while being dedicated to our project. His laboratory experience, combined with detailed work and experimental assistance, enabled the successful lab work for this research project. His support has proved essential to everything related to experimental work because he made sure all the required equipment was ready and provided crucial information about laboratory methods. My gratitude extends to his patience and dedication.

Artificial Intelligence systems were employed for clearing up the content and fixing grammatical errors in this document. The entire content, alongside its interpretations, is original work of mine.

I want to acknowledge that I have done my part of the work, showing dedication and perseverance during this research. Conducting this study has been challenging and rewarding, as I have learned and continued to solve problems in the process of learningThrough this academic endeavor, I developed resilience, and I can take pride in the progress I have made.

I would also like to express my gratitude to all those men and women who helped me with this journey, either directly or indirectly. Without the support and guidance from the collective, none of this would have been possible, and I want to thank the individual whose role has helped make this research a reality.

Thank you all.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

Formation damage is one of the most significant challenges in managing oil reservoirs, as it impacts recovery and the long-term productivity of fields. It occurs due to unfavorable interactions between rock particles and reservoir fluids, often triggered by fluid flow or operations such as drilling, completion, and injection. Physical or chemical changes within the reservoir caused by formation damage can lead to a decrease in hydrocarbon recovery and significant management challenges.

The negative changes in the reservoir due to formation damage can result in high operational costs, possible production problems, and reduced productivity. The procedure of drilling mud injection modifies fluid behavior and obstructs rock pore channels, which produces permeability reduction. The process of enhanced oil recovery using water or chemical injections produces destabilized fine particles that move to block pore channels. Early detection and prevention of formation deterioration must become essential steps since they ensure reservoir performance alongside effective oil recovery.

Formation damage results from the movement of fine particles as an underlying damage-causing factor. The process of migration of fines includes clay particle detachment from rock contact, followed by their travel through rock channels, which eventually leads to pore blockage and degradation of permeability. Yang et al. (2022) establish that several operational triggers cause fine particle migration, including interaction between injection water and formation fluids, and drilling and completion fluid infiltration and high-rate oil and gas production (Mungan, 1965; Muneer et al., 2022). In all these cases, the detached fines act as barriers between the rock surface and fluids, leading to unsteady flow and reduced permeability, as schematically shown in Figure 1.1.

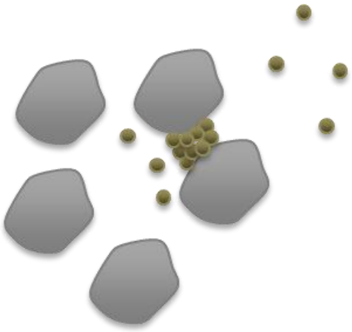

Figure 1.1 Permeability reduction by blocking the pores

Rock permeability decreases due to pore space blocking when small particles such as kaolinite, montmorillonite, and illite move into position during the process (Yang et al., 2022). The conditions of fresh water injection provide the right environment for fluid flow redirection into fields unexploded during production. The observed sequence indicates that while fines migration normally harms reservoir permeability, it sometimes presents beneficial outcomes. Studies by Al-Sarihi (2018) demonstrated delayed permeability decrease because it resulted in extra oil recovery through the process of fines release. The researchers connected this outcome to the partial blocking of pores which limited fluid mobility while steering fluids toward unflooded regions (Sarkar & Sharma, 1990). The advantage in oil production from formation instability works as a short-term solution yet leads to permanent recovery reduction because the unstable particles interfere with long-term production. Overall, fines migration, a form of formation damage, presents operational challenges and risks that often outweigh its benefits.

Certain EOR methods exacerbate fines migration by destabilizing formation particles. The effectiveness of water or chemical flooding procedures worsens the problem. The chemical EOR method known as low-salinity water flooding causes decisions in salt content that destabilizes clay materials leading to their movement. In the same vein, the pore structure changes, and clay stability patterns shift as a result of performing steam flooding which belongs to the thermal EOR category. When mobilized fines reach pore openings these events cause pore throat blockage which results in decreased formation permeability.

Alkaline water flooding serves as an EOR mechanism mainly directed toward enhancing oil recovery from sandstone deposits. Injecting water with alkaline solutions creates a chemical reaction between the water and acidic parts of crude oil to decrease interfacial tension and recover trapped oil, according to Zhong et al. (2020) and Gong et al. (2016), and Sheng (2013). Chatterjee & Wasan (1998), together with Gong et al. (2016), demonstrated how elevated pH levels in alkaline flooding affect interfacial tension to increase oil recovery rates. Zhong et al. (2020) reported that alkaline flooding tends to release formation-damaging fines due to its processes. The drilled reservoir permeability gets changed through physical and chemical interactions between rock surfaces and introduced fluids, which generate identical breakdown patterns to reduced salinity effects. High-pH water injection procedures frequently result in fines being separated from formation material and making them available for movement, which can form obstructions in pores.

Fines migration relies on several reservoir and fluid elements but pH stands as the key factor for sandstone reservoirs since minor changes affect how effectively fines release and move through the system. By changing water solution pH value to high levels the bond between rocks and fluids weakens therefore enabling the separation of fines from the rock structure. Saturation maintains itself as a key factor with corporation from acidity and flow rate and wettability. These parameters form a complete system that decides how fines are set free and their ability to move, resulting in either boosted or diminished EOR performance. Higher water velocities create detachment forces that detach fines from rocks because salt concentrations both affect how fines stick to the rock and their stability. The stability of fines decreases in low salinity conditions, while the attachment between rocks and fines improves at high salinity rates. Fluid injection causes wettability changes which consequently affect the stability of fines and their mobility rates. To achieve accurate predictions of the possibility of fines migration all important parameters must be analyzed together. Correct forecasting of fines migration remains crucial because it enables both formation protection and optimized reservoir management practices. The Derjaguin Landau Verwey, and Overbeek theory serves as a fundamental system that evaluates the forces that govern how particles interact with each other. The method serves as a tool to evaluate how fines react with rock surfaces in porous media structures. The model analyzes electrostatic and van der Waals forces simultaneously with non-specific forces, which have their source from fluid flow behavior. The DLVO model enables predictions about the behavior of fines that occur under different environmental conditions, including high pH, low salinity, and high rate.

Fine release becomes effective in certain pH conditions before pore blockages lead to permeability decline. The analysis of reservoir conditions together with DLVO modeling helps to optimize EOR processes and improve the recovery while controlling fines migration. The objective remains to identify the critical areas of detaching fines through specific salinity and pH ranges. Precise fines migration prediction plays a fundamental role in reducing economic risks during production operations. Formation damage produces financial expenses as well as operational decreases in performance. The implementation of modeling tools such as the DLVO theory offers reservoir engineers both behavioral understanding of fines and the capability to create new EOR approaches.

1.1 Problem Definition

The extraction of hydrocarbons from sandstone reservoirs stands as an essential operational goal within the oil and gas sector. The worldwide energy reserves contain valuable segments due to their presence in these reservoirs. Sandstone reservoirs face two primary obstacles when it comes to hydrocarbon retrieval because of fines migration. Very small sediment grains, including clay and silt, together with other related minerals, migrate away from their natural habitats through the process known as fines migration. Small particles that become mobile through the process create pore blockages, which diminish permeability until extraction rates decrease.

Preventing permeability loss remains essential in hydrocarbon production because it threatens the success of water flooding techniques. Fines migration leads to both scientific and economic importance because it relates to environmental risks like toxic waste disposal and embankment failure incidents. The physical characteristics and chemical makeup of injectate fluids combined with comprehension of the influencing forces need thorough study to solve challenges in fines release and movement during recovery operations.

A porous rock matrix can experience fundamental mechanisms that contribute to fines migration when fluids pass through it. The movement of fines in physicochemical parameters is affected by various changed environmental factors. The management of fines migration depends on the pH value since it impacts how particles move through the rock matrix. A multitude of studies reveal that the solution pH directly controls the strength of forces that bind fines to rock particles. The adhesive or detachable nature of fines under reservoir conditions depends on the following forces: van der Waals attraction, electrostatic repulsion, and Born repulsion. The release point of fines occurs when adhesive forces are surpassed, which corresponds to a solution's "critical pH". The precise identification of critical pH values enables optimal optimization of water injection as well as EOR processes, together with acidizing operations.

The determination of critical pH in sandstone reservoirs constitutes an important operational challenge despite its recognized importance. The critical pH represents a dynamic condition resulting from the surface chemistry relationships between rocks and clay-sized particles. A system containing multiple interactive components develops from the combination of ion adsorption and desorption processes and measurements of zeta potential and surface charge at various pH values. Therefore, a thorough understanding of colloidal forces, as described by the DLVO theory, is necessary. This theory combines van der Waals and electrostatic interactions to explain the behavior of particles in suspension.

The DLVO theory can help describe the impact of these forces, allowing for an estimation of formation damage and how it can be controlled. It is important to note that pH is one of the fluid parameters that affects modeling under the DLVO theory, but its influence varies across different cases. Previous studies have shown that high, alkaline pH can cause clay particle migration during low-salinity water injection, highlighting the need to simultaneously study the interconnection between salinity and pH in order to minimize formation damage. However, there is still a lack of information in the literature regarding fines migration affected by pH during DLVO modeling on a particle scale. Additionally, there is no comprehensive modeling for the critical flow rate that accounts for electrostatic, gravitational, and hydrodynamic forces, which could precisely estimate the critical injection rate for initiating fine migration in subsurface sandstone formations. While some discrete critical flow rate models exist, they describe lifting and rolling mechanisms separately for fine migration in different salinity systems.

The experimental and modeling analysis determines the critical pH at which fines begin their release and migration process. The main question is how to apply the DLVO theory for pH measurement and effects quantification. The study includes methods to compute forces that facilitate fine migration in reservoirs containing crude oil and how to determine essential requirements for these forces.

The prediction of sandstone reservoir fine migration initiation through critical pH analysis presents an essential problem for reservoir management and hydrocarbon recovery. The resolution of this challenge promotes reservoir operations that are more efficient and sustainable and cost-effective.

1.2 Objectives of the Thesis

1.2.1 Main Objectives

The main objective of this work is to study the DLVO model to predict the critical pH effect that initiates fines migration in sandstone reservoirs. The approach considers several fluid parameters that affect the sand-fine-brine system, such as the pH and injection rate of the fluid. During the change of these parameters in the system, surface forces eventually change, which leads to the release of fines in reservoirs.

Based on the studies reviewed, the following objectives are the focus of this work:

To predict the critical parameters, such as pH and flow rate, using the DLVO modeling technique once surface forces have been quantified.

To make a comparison with actual experimental data to provide validation of the generated models.

1.2.2 Specific Objectives

A theoretical model using DLVO theory will be developed to determine conditions that result in particle detachment due to electrostatic and van der Waals forces. The critical pH threshold that influences critical pH will be observed during core flooding tests and will be compared to the effects of flow rate. Rock fluid electrostatic interactions will be quantified through zeta potential measurements, while the study on the impact of ionic strength and ion type on the critical pH will reveal how ions reduce fines stability. This will serve to provide insights into the formation damage mechanisms and will recommend how injection water chemistry can be optimized to mitigate the fines migration risks in oil reservoirs.

1.3 Scope of Work

The research objective involves predicting sandstone reservoir critical pH for fines migration using the DLVO model while executing experimental core flooding across various flow rates to verify predictions. The research has two objectives: establishing a theoretical model for calculating electrostatic and van der Waals forces that detach fines and specifically determining optimal conditions of pH levels and flow velocities needed for mobilization. Core flooding tests under high and low flow rates will monitor fines migration, allowing researchers to validate experimental critical pH and flow rate with predicted values from the DLVO model. Zeta potential and streaming potential measurements will evaluate rock-fluid electrostatic interactions as the pH condition is modulated. The research examines how brine salinity with monovalent and divalent cations influences the detachment behavior of fines during the study. Experimental data comparison with model predictions will determine how effectively DLVO modeling supports formation damage research and helps develop optimized water chemistry solutions to reduce fines migration in oil reservoirs.

2. LITERATURE REVIEW

Water injection, commonly referred to as water flooding, is a secondary recovery technique designed to inject water into reservoirs through strategically drilled injection wells. This method facilitates oil displacement while simultaneously increasing reservoir pressure to counteract depletion. However, water flooding, like EOR methods, alters the chemical and fluid properties of the reservoir, potentially disrupting its equilibrium.

Naturally, reservoirs exist in a state of mechanical and chemical balance. The interaction between minerals, reservoir rocks, and formation fluids maintains this equilibrium. The introduction of external fluids through EOR or water flooding processes can disturb this balance for several reasons. The chemical reactions between injection fluids and natural fluids present in reservoir rocks represent the initial issue. Clay minerals experience swelling and detachment when they meet brine, leading to the distribution of fine particles throughout the reservoir. Extended water flooding injection rates produce drill forces that move fine particles comprising clays and additional minerals from their reservoirs. The transport of these particles results in permeability reduction because they block pore spaces, which diminishes oil extraction performance. The combination of chemical reactions and mechanical transfers, and particle movement forms the process known as fines migration.

The phenomenon known as fines migration leads to substantial drops in reservoir permeability, thus creating major problems during water flooding/EOR operations. Physical and chemical aspects within the injected fluid control the reservoir equilibrium as well as fines responses. The weak binding force between clay particles and rock surfaces occurs when using low-salinity water flooding (LSWF) because the ion strength changes. Mobilized fines migrate to pore throats and create obstruction, leading to permeability decline and poor well injectivity, and wellbore blockage near the production area.

The migration of rock fines highly depends on pH variations in the reservoir system. Fluids with modified pH levels change mineral decomposition and formation dynamics because they affect the electrostatic properties of mineral material surfaces, which causes mineral particles to detach. Fine migration tends to worsen due to destabilization, which leads to decreased efficiency in oil recovery. The knowledge of complete injection fluid parameters becomes vital for controlling fines migration during water flooding/EOR operations. The modification of pH values along with salinity adjustment produces better recovery results in oil fields without breaking reservoir chemical balance.

2.1 Parameters Affecting Fines Migration

Sandstone reservoirs represent one of the biggest accumulation points of oil and gas resources. The rock structures in these reservoirs mainly contain sand grains and clay particles on their surfaces, while oil or water exists between the void spaces of the rock framework (Chavan et al., 2019). During oil production and under specific chemical situations, the instability of clay particles in sandstone formations can develop. The structural balance of clay particle surfaces deteriorates after fluids enter reservoirs that differ in composition from natural reservoir materials. The decrease in the negative surface charge of the rock material during LSWF destabilizes clays while they swell up. The application of LSWF proves successful for improving oil extraction when particular criteria are met. The application of LSWF requires clay particles in sandstone reservoirs according to Austad et al. (2010). Many authors support that LSW enhances oil recovery, but researchers also confirm that permeability might diminish due to water injection-triggered clay movement linked with pH alterations and subsequent swelling of clays, which eventually leads to permeability decrease (Austad et al., 2010; Nasralla et al., 2011; Mehdizad et al., 2022).

The experimental results showed that solution pH levels contributed to altering the rate of fines migration. Kia et al. (1984), together with Vaidya & Fogler (1992), discovered that permeability reduction tends to start at pH levels of 3.6 and 2.6, respectively. The results from their study demonstrate that permeability reaches specific pH levels due to the movement of clay material contained within sandstone reservoirs. When the pH level increases, the surface-active components on clay particles develop decreased negative charge that reduces repulsive forces, thus enabling their detachment from the surface. High ionic content in injected water speeds up the destabilization process. Research conducted by Vaidya & Fogler (1992) has shown that clay destabilization occurs at pH 2.6 when no counter-ions are present in salt-free solutions, as reported in their article, but the study by Kia et al recorded permeability loss at pH 3.6. In summary, the detachments of fines depend on both solution pH and salinity strengths.

Pore throats experience clogging by detached clay particles, which creates flow disruption together with permeability reduction. Reservoir rock structures become irreversibly altered because clay mineral swelling occurs at high pH conditions, which also decreases porosity. Clay swelling as well as related formation damage, can occur when LSWF triggers pH elevation. The study outcomes reveal that reservoir behavior and fine migration patterns strongly depend on pH value while clay mineral composition, together with salt concentration matter significantly.

Vaidya & Fogler (1992) investigated how rock-fluid chemical interactions shaped the relationships between water salinity and formation damage and pH values. The researchers established that when pH levels are elevated while saline water is reduced formation damage becomes more severe. Fresh water injection with a pH of two did not affect permeability but the formation permeability declined considerably at pH levels higher than eleven. Research studies from Yang et al. (2022) and Ma et al. (2020) showed that permeability stability occurs during low-pH situations but decreases with increasing pH conditions. The authors Muneer et al. (2020) and Ma et al. (2020) demonstrated that neutral-pH water made with saline would reduce fines migration.

Muneer et al. (2020), together with Gao et al. (2004), discovered that particle mobilization arises from repulsive forces when using alkaline pH solutions. Experimental tests conducted under high-pH NaCl salt solutions validated the observation of this phenomenon. The research showed that kaolinite clay particles bind with OH- ions, resulting in diminished clay surface negativity, which causes OH- ions to move away from the surface and decrease repulsive forces. Clay surfaces under pH 7 exhibit an increased distribution of cations and OH- while adsorbing both species, which strengthens repulsive forces toward the rock base, leading to clay swelling according to Ma et al. (2020).

The interactions between rock and fluid systems depend on wettability factors as they largely determine how injected water properties affect the recovery process. Sheng (2013) showed how modifying wettability when dealing with water salinity enhances recovery performance. According to Muneer et al. (2020) and Askar et al. (2023) the process of fines migration becomes more intense in water-wet areas when LSW injection methods are employed. High-salinity brine demonstrates a potential ability to restrict fines movement in weakly water-wet rock environments through its protective action on moving fines. The interaction between salt content in the water and what occurs with fines and rock contact demonstrates which properties determine how much oil can be recovered from flooding operations.

Tang et al. (1999) examined how water salinity affects oil recovery rates alongside how changes in fines affect water flooding cycles. The research showed that saline levels did not affect oil recovery directly, but brine injection strongly altered both rock conditions and fine behaviors. The experimental data showed that as flooding cycles continued, fines release became progressively less due to an interrelated relationship between wettability modifications and water saturation distribution. The study demonstrates the importance of addressing both chemical and physical aspects when trying to maximize oil extraction.

The movement of such particles represents a major threat to formations because it leads to damage that affects permeability and compromises production effectiveness. The migrating particles develop accumulations at pore throats, thereby creating obstacles that restrict fluid movement. Formation damage depends on how saline and what composition the injected water contains, along with clay mineral patterns and how wet the reservoir is to begin with. High-salinity water injections can suppress fines migration by increasing electrostatic attraction between particles and rock surfaces. Conversely, LSW leads to enhanced fines release by altering electric double-layer forces at the rock-fluid interface, as discussed by Nasralla et al. (2013).

The relationship between wettability and formation damage involves changes in surface charge during waterflooding. Surface charge is determined by the adsorption of ions, particularly negatively charged ions, onto the particle surface. LSW reduces brine ionic strength, increasing electrostatic repulsion between negatively charged rock surfaces and clay particles. Barnaji et al. (2016) demonstrated that injecting high-pH LSW improved oil recovery through increased fines migration. As shown in Figure 2.1, the reduced cation concentration in the solution forces clay to adsorb cations from the diffuse layer, increasing repulsive forces. While LSW may enhance water-wetness and improve recovery by reducing the contact angle at the rock-fluid interface, the concurrent release of fines can negate these benefits by clogging pore spaces and reducing permeability. This dual effect highlights the need for a balanced approach to wettability alteration and fines control in enhanced oil recovery operations.

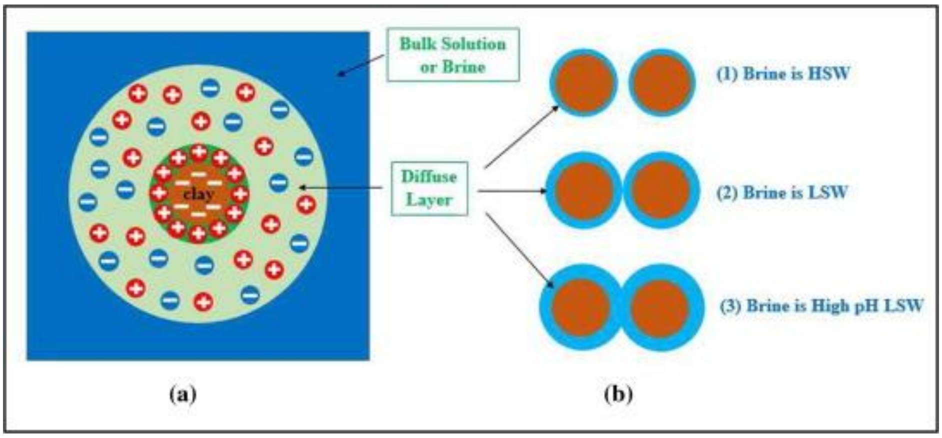

Figure 2.1 Impact of pH and salinity on clay particle and diffuse layer (Barnaji et al. 2016)

Subsequent research by Assef et al. (2014) and Barnaji et al. (2016) investigated the impact of LSWF on fines behavior. The change in equilibrium of rock surface and in situ fluids may alter the wettability of the rock system, diminishing colloidal attractive forces between oil and rock. Assef et al. (2014) contended that brine injection might inhibit the release and migration of clay particles. Barnaji et al. (2016) conversely emphasized that increased oil recovery is absent in systems without clay minerals since connate water and clay minerals inhibit adherence to the surfaces of porous media. In these instances, fluid dynamics and water salinity had little influence on recovery efficiency. In porous systems devoid of connate water but retaining clay minerals, there exists potential for enhanced wettability and oil recovery, highlighting the essential influence of mineralogy and fluid interactions. Overall, there is a high connection between parameters such as wettability and salinity of water, where salinity with the ionic composition of water impacts surface forces, which impacts oil recovery efficiency. These results indicate the need for customized water injection tactics according to reservoir-specific attributes.

The interaction among wettability, fine release, and formation deterioration is a critical aspect of reservoir management. Wettability directly influences the stability of fines, while variations in water salinity can alter wettability and promote fines migration. LSWF has shown promising outcomes as a wettability modifier, yet it remains a subject of concern because it triggers formation damage through the migration of fines.

High temperatures inside reservoirs act as an important element that encourages the movement of fine particles. High-temperature reservoirs have their renowned fines migration controlled by fluid property alterations as well as mineral-to-mineral interactions. High temperature-induced permeability loss can recover when temperatures decrease, even though salinity changes create a permanent pore throat blockage from migrated particles (Rosenbrand et al., 2014). Heat-induced changes in porosity and permeability that stem from surface water-layer reduction and thermal expansion do not adequately account for all measured permeability variations. Different studies about temperature effects on fines migration produce conflicting results. You et al. (2019) discovered that higher geothermal reservoirs experience higher rates of fines migration relative to traditional oil resources because heat weakens formation permeability. According to Yan et al. (2015), hot water injection produces stronger clay-rock surface attractions because repulsion forces between colloidal particles match and surpass attraction forces. The conflicting findings about these effects could stem from the connection existing between reservoir temperature levels and fluid pH values.

A Madadizadeh et al. (2022) examined temperature effects on pH values which affected the migration behavior of clay particles. Continuous increases in temperature showed bigger impacts on linear migration at pH level 12 when compared to the effects at pH level 8. The effect of temperature on migration becomes stronger as the pH levels increase. Temperature increases led Musharova and colleagues (2012) to observe changes in pH values. Their study also demonstrated that high-salinity salt solutions could preserve rock permeability and reduce fines mobility during temperature declines, emphasizing the importance of injecting brines with elevated salinity concentrations.

Wang et al. (2021) studied the combined effects of temperature and salinity on fines migration and the consequent permeability reduction. Their research revealed that injecting NaCl brine into Berea core samples caused a 99% permeability decline at 25 °C, compared to only a 40% reduction at 70 °C. This suggests that ion exchange reactions involving Na ions play a pivotal role in fines migration and permeability loss. At 25 °C, the absence of competing ion exchange reactions with NaCl led to enhanced fines migration and a substantial permeability decrease (Figure 2.2). Figure 2.3 indicates that normalized permeability (k/k₀) and fines concentration varied with pore volume injected (PVI), with significant fines production primarily observed in the lower salinity stages at 70 °C. At 25 °C, permeability consistently declined with decreasing salinity.

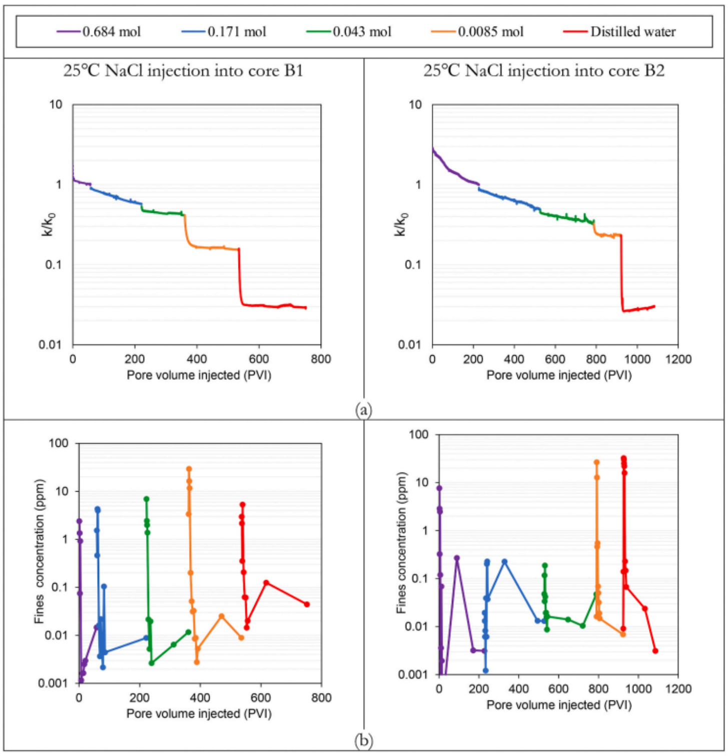

Figure 2.2 The change of permeability and fines concentration during room temperature (Wang et al., 2021)

These findings align with prior research indicating that reduced salinity promotes fines migration and decreases permeability. However, the extent of fines migration and mineral interactions also depends on temperature, which can have varied effects on system stability. This highlights the multifaceted impact of thermal, chemical, and physical factors on fine migration and reservoir performance. A thorough consideration of these factors is imperative for effective reservoir management and optimized oil recovery.

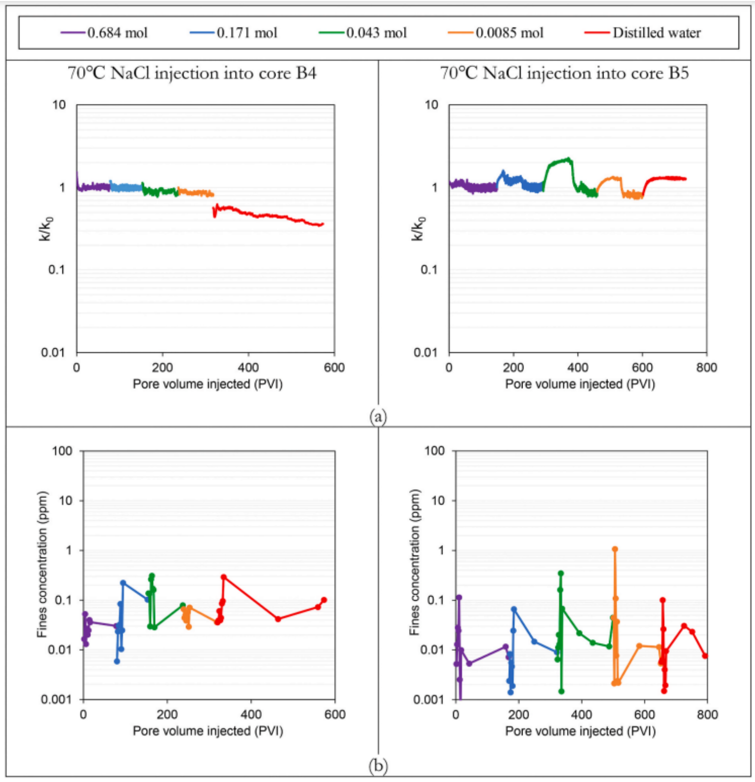

Figure 2.3 The change of permeability and fines concentration during the 70°C (Wang et al., 2021)

Another parameter that may explain the decrease in permeability during alkaline flooding is the flow rate of injection fluid. Bradford et al. (2013) suggested that the mobility of clay particles happens during the unstable high-velocity fluid flow. After the high rate of fluid injection, clay particles are released; they move into the pore space of the rock, where pores trap them and prevent their further movement. Muneer et al. (2023) suggested that a high pH value may also lead to fines release even at a low fluid rate. Despite this, Johnson et al. (2010) observed that neutral pH can be negligible in fines moving during buffered salt water, no matter which velocity.

Nevertheless, the fluid rate decreases the permeability more if the injection fluid is salt-free. Khilar and Fogler (1998) and Musharova et al. (2012) mentioned that migration can happen even at low velocity during freshwater flooding. For example, Ochi et al. (1998) and Muneer et al. (2023) studied the fluid rate when a fine release occurs, which is higher when the water is less salty and has a high pH value. Consequently, the heterogeneous chemical composition significantly impacts the origin of fines.

Despite this, Ji et al. (2023) mentioned that some synthetic fluids move better at low pH and slow down at neutral and high pH due to the presence of kaolinite particles in rock composition. As shown in Figure 2.4, breakthrough curves for the transfer of two fluids (a, b) under different pH conditions were plotted by comparing the relative effluent concentration (C/C_0) to solution volume. Their pH sensitivity to concentration varies significantly. Increasing pH led to a rise in relative effluent concentration ($P < 0.05$), with a concentration exceeding 0.9 over the pH range examined. As pH increased, the quantity of fluid compounds in the neutral form declined while that in the ionic form increased. This resulted in a reduction in the hydrophobic force and a rise in the repulsive force between fluid and sand, promoting its further transport.

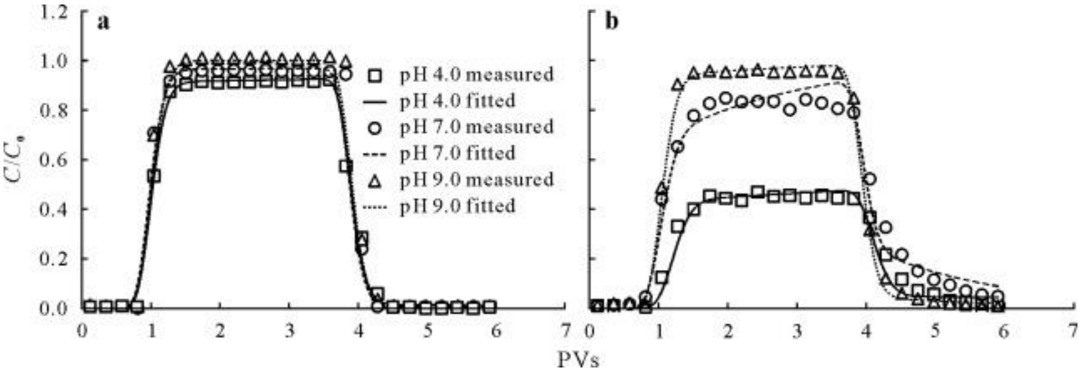

Figure 2.4 Sensitivity of the concentration of synthetic liquid to pH (Ji et al., 2023)

The relationship between velocity, temperature, pH, ionic strength, and particle repulsion in rock systems is proportional to the difference between these parameters and their critical values. The critical value indicates when fines start to release into the reservoir environment (You et al., 2019). The excessive elevation of vital thresholds by changes in fluid and rock properties inside reservoirs leads to clay repulsion. The process of fines migration emerges whenever injection-fluid parameters surpass their critical point values. A fundamental issue emerges regarding the methods to establish the possible extent of fines migration. Research conducted by Muneer et al. in 2020 and 2022 produced significant critical factors that experimental studies later confirmed.

The Critical Salinity Concentration (CSC) served as a research technique to evaluate water salinity's impact on particle release and migration. Fines become mobilized from the rock surface as water salinity drops beneath the Critical Salinity Concentration, according to Khilar & Fogler (1984) and Mansour et al. (2020). Muneer et al. (2020) conducted experimental validation by studying rock and fluid compositions in their study. The Derjaguin–Landau–Verwey–Overbeek (DLVO) model enabled the prediction of the Critical Salinity Concentration

(CSC) because it determines the detachment energy and mechanical motions of rock system particles. Repulsive forces according to the DLVO model help break the connection of clay particles with the rock surface, which allows their detachment.

The DLVO theory served as a basis for Musharova et al. (2012) while they studied forces acting on particles during experiments. DLVO theory provides a sufficient explanation to describe the behavior of fine-sand-brine-crude oil systems according to their research. The research demonstrated that electric double-layer repulsion forces resulted in diminished fines migration effects as well as reduced permeability levels.

According to Muneer et al. (2020), ionic strength functions as a significant chemical water property that affects fines migration through the CSC. In aqueous solutions, the CSC changes when divalent ions are present because they reduce the CSC value. pH joins ionic strength in modifying the behavior of the interfacial phenomena. The pH relationship with ionic strength decides which migration processes can be considered acceptable. A rise in pH level in saltwater produces electrical negativity on the rock surface. The ionic fluid conditions and permeability of a fluid rely heavily on the combination of pH and CSC values as essential parameters.

2.2 Approaches to Predict Fines Migration Initiation

The initiation of fines migration can be predicted through identifying the specific critical conditions that drive fines detachment by salinity variations and pH changes, as well as flow rate and temperature. Research demonstrates that direct measurement occurs through coreflood tests combined with effluent analysis, although modeling uses computational approaches together with theoretical DLVO-based calculations for predicting fines detachment points.

Karazincir et al. (2017) performed multiple laboratory evaluations that aimed to improve fines migration forecasts while determining specific conditions that control the occurrence of such phenomena. The core tests resulted in verification of fines migration occurrence during experiments, which used an increased productivity index and reduced skin factor following diesel injection. Core tests performed by the researchers did not detect fines migration everywhere, even when using samples from the same reservoir formation. The experimental forecast of fines migration relies on multiple elements such as fluid type and amount, along with testing temperature and sudden changes or depletion states according to Karazincir et al. (2017).

The authors at Bagrezaie et al. (2022) completed experiments to confirm the validity of fines migration models. The authors implemented User-Defined Functions (UDF) into the standard Discrete Phase Model (DPM) available in ANSYS FLUENT software. The software enhancement made better two-dimensional (2D) microchannel fine particle movement simulation achievable by using pressure drop information based on pore volume insertions. The simulation-generated data enabled developers to create an artificial neural network (ANN) proxy model, which provided high accuracy with reduced computational expenses. The simulation performed faster calculations through the utilization of the rain optimization algorithm (ROA). Experimental tests performed with glass micromodels showed that the model was accurate by applying calcium carbonate powder suspensions. The experimental outcomes revealed that decreases in particle size, together with higher amounts of particles, enhanced both pressure drop levels and permeability reduction effects.

Chequer et al. (2021) performed an analysis of different well stimulation methods and their ability to cause harm during various operational phases. The acid treatment methodology documented how fine particles emitted from rocks will cause formation damage, particularly in geothermal areas when water salinity remains low. Periodic measurements of particle size distribution served as the identifying feature for monitoring the fines migration system present in produced water. Clogging ratio measurements showed which particles came from either the reservoir matrix or well wall through the inclusion of these results in the clogging ratio calculations. Through this methodology technicians gained knowledge about both the formation damage area dimensions and basic recommendations for acid treatments along with optimized perforation designs. The optimization process remains vital for decreasing both economic expenses and operational expenses related to elongated well acidizing procedures while shortening shutdown periods. A proper evaluation of parameters needs to occur before implementing the model because DLVO theory can help validate the particle-rock attraction assumption.

Musharova et al. (2012) conducted coreflood experiments to assess the effect of temperature on clay release from the sand surface and verified it by DLVO theory. During the test, the temperature gradually increased to 74°F, 200°F, and 300°F to observe its effect on the fines migration and permeability. Then, based on the findings, the system at 300°F is damaged much more rapidly than its identical system at 74°F. The verified model of DLVO is then used to predict fines detachment during coreflood tests, which have demonstrated that under certain conditions (e.g. changes of temperature, salinity, or pH), repulsion force is dominant, especially in matrix clays systems.

2.3 DLVO: Forces and Critical Parameters

To understand the origin of particle interactions, it is necessary to introduce four fundamental forces. The first is the weakest force, associated with interactions among subatomic particles that govern the radioactive decay of atoms. The second is the strong force, which binds quarks tightly within protons and neutrons and also facilitates the binding of protons and neutrons to form atomic nuclei. The third is the gravitational force, which represents a weak interaction affecting energy. The final force is electromagnetism, which governs interactions between charged particles. Among these, electromagnetism is the most relevant to chemical processes, as it dictates the interactions between atoms and molecules. In condensed phases such as liquids and solids, electromagnetic forces alone determine the existence and behavior of these phases.

According to Russel et al. (2018), the detachment and transport of particles in porous media are governed by several forces (Figure 2.5). Charges on particles and the pore walls create electrostatic effects (F_d). For example, repulsive forces may prevent adhesion of negatively charged particles and surfaces, and attractive forces may cause adhesion. Large particles, however, are influenced by other forces, such as gravity (Fg), which push them to migrate to settle inside pores because of their weight.

The attachment or aggregation of particles on pore walls relies on electrostatic attraction forces, which are generally short-range. In addition to exhibiting an electrical double layer (EDL), which comprises the Stern layer, in turn affecting the stability of suspended particles, and a diffuse layer around it. At low electrolyte concentrations, repulsive EDL interactions can lead to fines migration in regions of double layer overlap, particularly where these double layers overlap.

In contrast, when high flow velocities and shear stresses exist, hydrodynamic forces contributing to particle adherence removal are drag (F_d) and lift (F_L). The kinetic behavior of particles inside porous structure is driven by these forces; the values of these forces depend on such factors as porosity, salinity, flow rate, and particle size.

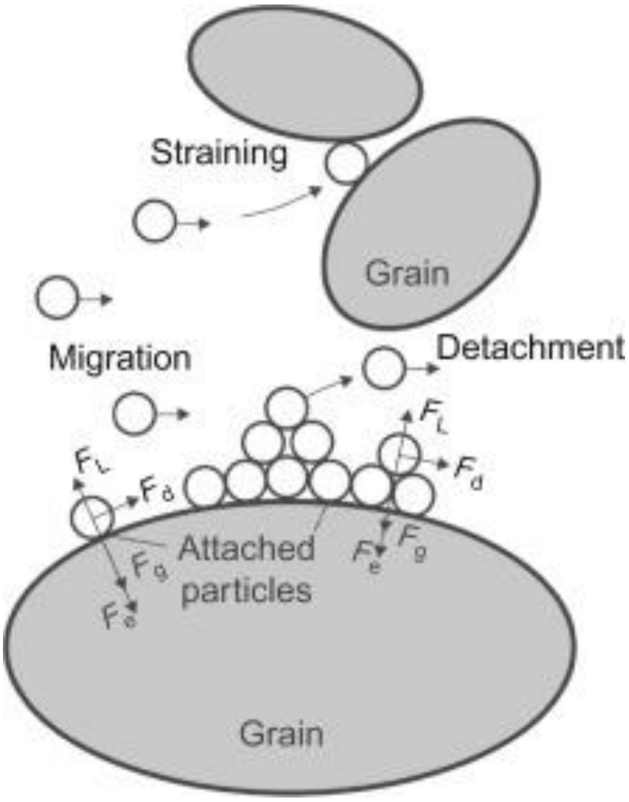

Figure 2.5 Impact of forces on the detachment of the fines particles from the rock surface (Russel et al., 2018)

Particle collisions in a sand-brine-fine system occur due to uncontrolled particle movement and gravity. When colloidal particles are in close proximity to one another, they are influenced by van der Waals attraction forces. However, without counteracting forces, the system becomes destabilized. A colloidal system achieves stability when there is a balance between attraction and repulsion forces, similar to mechanical equilibrium.

DLVO theory provides a conceptual framework for describing interactions between surfaces separated by a liquid, particularly in colloidal systems. This theory is grounded in the laws of intermolecular forces, which are predominantly of electromagnetic origin (Hernandez, 2023). According to the DLVO theory, interactions are governed by two opposing forces: attraction and repulsion.

Van der Waals attraction forces arise from fluctuations in the electron distribution around molecules, leading to the formation of temporary dipoles and intermolecular attractive interactions. Conversely, repulsive electrostatic forces are due to the charge distribution on surfaces and in the surrounding liquid, especially when the surfaces are electrically charged. The stability and behavior of colloidal particles are determined by the equilibrium between these opposing forces. This equilibrium controls phenomena such as particle aggregation and the formation of stable systems.

Nevertheless, in predicting fines migration in porous systems, these interaction forces must be augmented by the hydrodynamic forces, such as drag and lift. Under dynamic conditions, these forces are also highly important for determining the motion of particles across surfaces.

2.3.1 Colloidal and Hydrodynamic Forces Impact on Fines Migration

It is important to note that fine migration has a huge impact on reservoir performance, since the particles, i.e., clay, can migrate and cause formation damage by filling pores and reducing rock permeability. In the presence of adhesive forces, such as those encountered near inlet walls, fines stay attached to surfaces. But they only mobilize when the hydrodynamic forces exceed the adhesive threshold. As the forces acting on them become repulsive, which is often if the particles are charged, Barnaji et al. (2016) have observed that fine particles tend to detach and migrate. Factors that influence this behavior are pH, flow rate, particle size, and charges of the system determining colloidal and hydrodynamic forces (Khilar & Fogler, 1987).

Rosenbrand et al. (2014) also state that particle repulsion from rock surfaces can increase with increasing negative charge of both rock and clay particles. This implies that clay instability caused by chemistry and the interaction between injected and produced fluids can give rise to fines migration. For example, Muneer et al. (2020) tied clay particle migration to changes in electrostatic forces that can occur during mud invasion in drilling, acidizing treatments, or water injection in reservoirs for enhanced recovery.

Therefore, to assess which forces dominate and whether particles are more affected by repulsion or attraction forces, a number of tests were carried out. When electrostatic and drag forces overpower van der Waals forces, the boundary layer of the fines is mobilized. Both the sand surface and fines particles are negatively charged, and so there is an electric double-layer force, as illustrated in Figure 2.6, that generates repulsion. However, the high ion content in formation water reduces the negative charge on both surfaces, allowing van der Waals forces to dominate and maintain the adhesion of fines to grain surfaces.

When fluid injections reduce the salinity of the system, the reduced ion concentration diminishes the neutralizing effect on the negative charge, leading to an increase in electric double-layer repulsion forces. As these repulsion forces surpass the van der Waals attraction forces, fines are released and begin to migrate. This phenomenon, described by Khilar and

Fogler (1984), highlights the role of colloidal forces in fine release and the influence of system properties on this process.

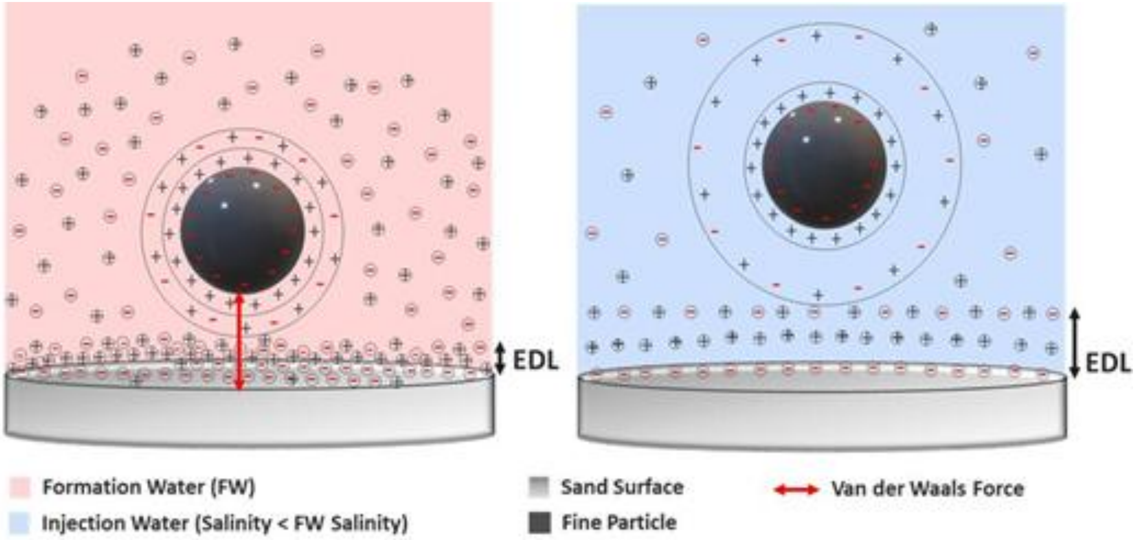

Figure 2.6 Fines mobility under attractive and repulsive forces

Simplifying the measurement of attraction forces between two closely positioned bodies as a function of their distance is one of the direct methods of studying the van der Waals theory (Israelachvili, 2011). In an experiment, glass was used to create two bodies, and the deflection of a balance arm measured the forces between them. The forces were observed in air and vacuum within the retarded regime. The experiment revealed that glass surfaces may not be reliable for separations smaller than approximately 10 nm. To address this limitation, Israelachvili (2011) suggested using fewer rigid surfaces, which could allow observations of surface separations as small as 0.1 nm. The theory of van der Waals is consistent with experimental results when using the measurements of films with wetting spaces or nonpolar liquids.

In addition, hydrodynamic forces are also important for the release of fines from rock surfaces. This process is closely related to the factors of particle size, injection fluid velocity, salinity, and pH. Muneer et al. (2023) studied fines migration under low and high rates of injection with consideration of the brine salinity and particle size. It was found that at low injection rates, electrostatic forces predominate over the detachment of clay particles from sand. Findings from this study indicate that fines release takes place in the presence of low salinity environments where the Debye length increases and electric double layer forces become stronger.

The size of fine particles had a significant effect on the destabilization of a system at higher injection rates. The van der Waals forces were more important for particles smaller than 500 microns, therefore requiring more hydrodynamic forces for detachment.

In a 0.25 M NaCl solution, fines were released at 6×10−2 m/s in an injection rate of 4×10−7 m. Under the same salinity conditions, the release rate for the particle radius of 1×10−6 m was 9×10−2 m/s (Figure 2.7).

In general, analysis of particle size enables the critical flow rate for the injected fluid to be derived, and related information on fines migration mechanisms can be derived.

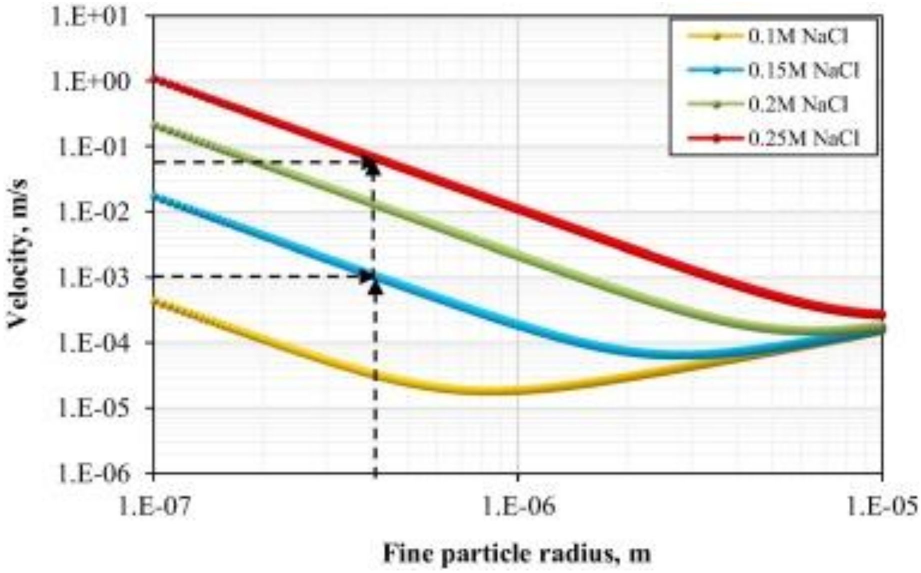

Figure 2.7 Effect of brine salinity and particle radius on critical injection velocity (Muneer et al., 2023)

Hydrodynamic forces were identified as one of the major driving forces of fines migration by Khilar and Fogler (1998), and in particular, because clay particles tend to swell and migrate under high fluid flow rates. Since the migration of fines is dependent on fluid flow rate, the fluid flow rate must stay below the critical limit. Muneer et al. (2020), Mansour et al. (2020) show that even when the separation distance between particles is the least, fine particles can experience forces in reservoir production and water injection.

In the experiments of Asef et al. (2014), a decrease in the migration of fine particles was observed using the DLVO theory, without taking into account the influence of hydrodynamic forces. In this study, acid-alkaline energy was used with a slug of MgO nanoparticles before alkaline flooding or freshwater injection. By stabilizing the system and minimizing fine release these nanoparticles were used.

In both cases, the pH of the injected water is important. However, it has to be optimized carefully to improve recovery efficiency and to avoid the fines migration. The framework of the DLVO theory is applicable to estimate the forces acting on fines release and movement of the fines through the colloidal particles in liquid and solid phases. Therefore utilizing this theory allows us to better understand and predict those forces that affect the fines migration process.

2.3.2 DLVO Theory

DLVO theory can estimate and control formation damage by quantifying surface forces that have a negative impact. According to Trefalt and Borkovec (2014), DLVO theory rationalizes forces that show particle deposition or can occur between interfaces (Figure 2.8). The authors explained that, initially, the theory was about only aggregating similar particles. Then, it was extended to another type of aggregation with different particles called heteroaggregation.

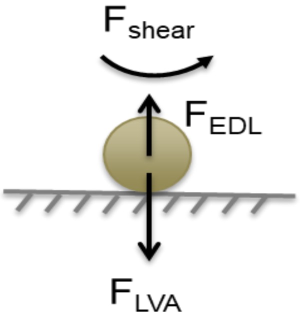

Figure 2.8 Balance between attractive and repulsive forces

Trefalt & Borkovec (2014), Muneer et al. (2020), Khilar and Fogler (1998), and Mansour et al. (2020) in their works, mentioned that the cumulative attractive van der Waals, repulsive Electric Double layer force, and Born forces that affect the particle movement could control fines migration.

$$V=V_{LVW}+V_{EDL}+V_{BR} \tag{2.1}$$

Hydrodynamic drag forces also play a significant role in the release of small particles. When the combined forces of electrostatic repulsion and drag surpass the attractive forces, these particles begin to detach and migrate. Typically, both sand grains and clay particles carry a negative charge, resulting in an electrostatic repulsive force acting between them.

In contrast, van der Waals forces, described by Muneer (2022) as the attractive interactions between two closely positioned bodies of similar nature, are present under most conditions. Trefalt and Borkovec (2014) observed that particle interactions are influenced by van der Waals forces, especially in environments with high salinity. In such cases, elevated van der Waals forces can promote particle aggregation, preventing migration.

To quantify this phenomenon, Sourani et al. (2014) utilized a formula that evaluates the forces between spherical and planar surfaces. In their analysis, they considered the sphere to represent fine particles and the plate to represent sand grains, providing a framework for understanding particle behavior in such systems.

$$V_{LVW} = A\,\frac{r_p}{6H} \qquad (2.2)$$

Where A is the Hamaker constant, r is particle radius, H is the distance between particles, and 1/6 is a derivation from integrating the van der Waals potential across the particle's volume.

However, van der Waals attraction variation may vary, and the way it works is based on particular models and assumptions that should be applied in the studies. There is also a formula, which was observed by Gregory (1981) for kaolinite platelets models:

$$V_{LVW} = -A\,\frac{a_p}{12H} \qquad (2.3)$$

Where a_p is the polarizability of the atom, and a negative value shows the attraction between substances.

According to the DLVO theory, fine particles demonstrate charge variations that affect the behavior of ionic strength and pH properties. Trefalt and Borkovec (2014) confirmed that reduced salt content in liquids enhances the reduction of double-layer forced particle aggregation. A set of electrostatic forces known as double-layer forces demonstrates that similar charges between particles repel one another. The fluid gets filled with suspended fines at lower ionic strength conditions because repulsive forces become more intense.

The movement of particles strongly depends on pH values in the solution. According to Muneer et al. (2020), elevated pH levels enable particle separation through repulsive forces and promote their movement in solution. Zeta potential served as an evaluative tool throughout their research to determine repulsive forces. The researchers found that positive zeta potential occurs in acidic solutions to strengthen inter-particle interaction, yet alkaline conditions enable weakening forces that cause particles to detach. The observed behavior tracks DLVO modeling since it matches the relationship between particle reactions and energy constituents of forces. According to Muneer et al. (2020), the energy system charge determines if fines will stick to rock surfaces by attractive forces or detach because of repulsive forces.

To define the electric double-layer forces, Sourani et al. (2014) used the formula:

$$V_{EDL} = \frac{\partial r_p}{4}\left[2\omega_{01}\omega_{02}\left(\frac{1+\exp(-kx)}{1-\exp(-kx)}\right) + (\omega_{01}^2 + \omega_{02}^2)\ln(1-\exp(-2kx))\right] \qquad (2.4)$$

$$k = \sqrt{\frac{e^2 I}{\varepsilon k_B T}} \qquad (2.5)$$

Where k_B is Boltzmann's constant, e is electron potential, k is reciprocal Debye length, I is ionic strength, and ω_{01} and $\omega_{02}$are the surface potentials of plate and sphere.

However, the surface potentials are difficult to measure; there is also another formula that can be described by constant potential:

$$V_{EDL}= 2\pi\varepsilon_m\varepsilon_0 a_p z^2 \ln\left(1 + e^{\frac{-h}{k^{-1}}}\right) \tag{2.6}$$

Where ε_m is the dielectric constant of water, ε_0 is the permittivity of vacuum, z is zeta potential, and e is the electron charge.

Despite the direct relationship between electric double-layer forces and particle repulsion, some studies have shown that these forces can be both repulsive and attractive (Trefalt & Borkovec, 2014). The behavior of this force depends on the system's aggregation. The authors found that double-layer forces can be attractive during heteroaggregation, which occurs when different types of particles are present. However, this attraction weakens as salt concentration increases (Latille et al., 2015; Trefalt & Borkovec, 2014). Additionally, mobility control in rock surface pores is more effective when low-salinity water is injected (Muneer et al., 2020; Trefalt & Borkovec, 2014). Liu et al. (2015) also studied particle heteroaggregation at neutral pH (pH = 7). This aggregation is typically associated with electrolyte concentration, which can vary between acidic and basic conditions. Overall, double electric forces can be both repulsive and attractive. However, their attractiveness is more prominent at low salt concentrations, which, as is well-known, can lead to formation damage.

Another repulsive force that affects clay particle migration is the Born repulsive potential. According to Muneer et al. (2022), Born repulsion occurs when particles are very close together and their electron clouds overlap. For instance, if the distance between particles exceeds 1 nm, it has little effect (Muneer et al., 2022; Yang et al., 2022; Mansour et al., 2020). Additionally, Israelachvili (2011) supports the van der Waals theory, which states that when the separation between surfaces is more than 5 nm, the Hamaker constant is effective. However, if the separation distance is less than 3 nm, the effect decreases by about 25%, which aligns with theoretical expectations. In this case, Born repulsion can be considered negligible. Yang et al. (2022) distinguished Born repulsion from EDL by its lower sensitivity to salinity compared to EDL. This distinction can be explained by the DLVO parameters, where EDL is represented by zeta potential, which is directly linked to salinity, while Born repulsion is determined by the Hamaker constant, which depends on particle size. Overall, the Born repulsive potential contributes to acceptable migration due to the overlap of grain and clay electron clouds. The Born repulsive potential was calculated using Equation 2.7.

$$V_{BR} = \frac{A_H}{7560}\left(\frac{\sigma}{a_p}\right)\left[\frac{8+H}{(2+H)^7} + \frac{6-H}{H^7}\right] \tag{2.7}$$

Fine detachment during the high flow rate can be affected by several forces such as hydrodynamic or drag force (F_d), lift force (F_l), electrostatic force (F_e), and gravity force (F_g), these forces are calculated using Equations 2.8, 2.9, 2.10. (Saffman, 1965, O'neill, 1968, Chrysikopoulos, 2014). The hydrodynamic force or drag force is parallel to the force acting on the surface of the rock, which displaces fine particles from the surface created by the fluid flow. The lift forces act perpendicular to the rock, potentially elevating the particle, while gravity forces attract the particle toward the ground to stick it to the surface. Then electrical forces come into play because of the rock and sand interaction, affecting the surface charge and ionic strength. These electrostatic forces result from surface charge and ion strength interactions between the particle and the sand surface and are presumed to partly oppose the gravitational force pulling the particle downward and enabling adhesion to the surface.

Figure 2.9 shows the balance of torques and forces affecting fine detachment, which helps to emphasize the dependence of thin deposition and further movement on this. Fines mobilization occurs when the detachment forces exceed the attachment forces. These dynamics are crucial for predicting fine particle mobility in applications like sediment transport, oil and gas reservoirs, and filtration procedures.

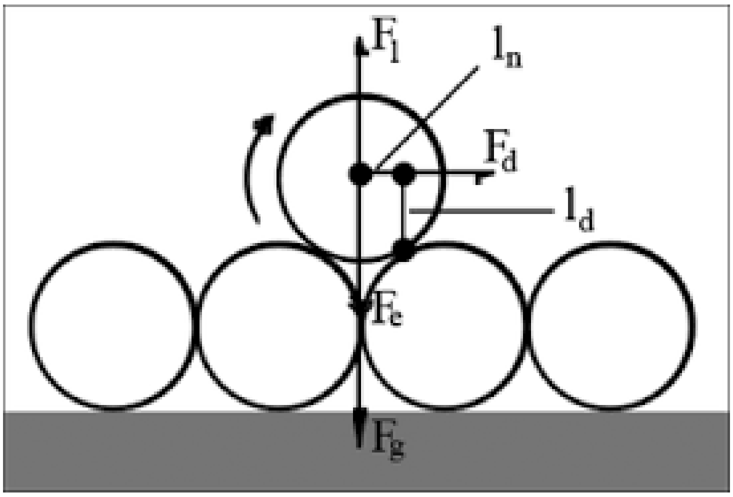

Figure 2.9 Acting forces of a fine particle on the surface of sand

$$F_d = 1.7009 \times 6\pi\mu r_f v_s \tag{2.8}$$

$$F_l = 81.2\sqrt{\rho\mu}\left(r_f v_s\right)^{1.5} \tag{2.9}$$

$$F_g = \frac{4}{3}\pi r_f^3\left(\rho_f - \rho\right)g \tag{2.10}$$

To consider the velocity profile of fluid flow in porous media around the fine particle, Equation 2.11 was used. In particular, it matches the velocity distribution of the creeping flow regime, such as the one governed by Stokes flow, which describes the conditions when inertial forces can be neglected from the system compared to viscous forces.

$$v_s = 2v\left(1 - \frac{\left(r_p - r_f\right)^2}{r_p^2}\right) \tag{2.11}$$

Conditions under which fines release will occure as shown in the Equation 2.12, where injection velocity are axceeding the critical rate. In this case, injection velocity contains the relation of drag forces, lift forces, external moment of the viscous stress, and fine particle radius.

$$10.21\pi\mu r_f v_s + 81.2\sqrt{\rho\mu}(r_f v_s)^{1.5} + 7.55\pi\mu v_s > F_g + F_e \tag{2.12}$$

Equations 2.11 and 2.12 were used to make the final equation, which generates the critical velocity profile for brine injection in porous media. However, during the low injection rate, the lift forces could be neglected compared to drag forces. Therefore, by considering forces that have an impact on fines detachment, Equation 2.13 was used to calculate the critical rate using DLVO modeling.

$$v = (F_g + F_e)\left[\frac{2r_f(2r_p - r_f)(17.75\pi\mu r_f)}{r_p^2}\right]^{-1} \tag{2.13}$$

Muneer et al. (2020) stressed the necessity to study and measure the various factors that shape this procedure. They studied how combining this knowledge and estimating critical pH can predict or even control clay swelling and release from sand grains. It becomes important to determine the factors which control the movement of clay particles.

2.4 Evaluation of parameters in DLVO to Predict Fines Migration Initiation

Since the DLVO theory is highly related to electrostatic forces, critical parameters may affect this theory's modeling. According to Sourani et al. (2014), Muneer et al. (2020), Yang et al. (2022), and Madadizadeh et al. (2022), parameters such as the size of the particle or Ionic strength (I_s), Hamaker constant (A_H), Zeta potential (z), pH of the solution, fluid temperature, Boltzmann constant, electron charge, and Avogadro's number may affect the fines migration.

2.4.1 Ionic Strength

Both Muneer et al. (2020) and Yang et al. (2022) analyzed how ionic strength (Is) together with particle dimensions affect double-layer energy (EDL) in colloidal systems. Electric double-layer energy represents the solution ion concentration through its thickness while solution ionic strength markers this thickness (Bohinc et al., 2001; Muneer et al., 2020). When ionic strength increases the Debye length (k) becomes thinner and makes the proper EDL thickness become insufficient. An increase in ionic strength reduces the Debye length according to Figure 2.10, which leads to enhanced particle deposition. The accumulation of counter-ions close to solid surfaces creates a decrease in electrostatic double layer thickness according to Compère et al. (2001). As a result, the likelihood of particle release into the solution decreases. Overall, these studies highlight how ionic strength influences particle deposition and release, with the decrease in deposition occurring due to the increase in Debye length, as these effects are reversible.

Ionic strength is a key parameter in DLVO modeling, as one of the application standards is that the size of all particles and the space between them should be the same. Fines become connected when the spacing between particles is less than the Debye length (Muneer et al., 2022). This is because the balance between attractive and repulsive forces is determined by the distance between particles. Trefalt & Borkovec (2014) explain that Van der Waals attractive forces dominate at both large and small distances, while double-layer forces prevail at intermediate distances. The authors suggest that this behavior can be explained by salt concentration and surface charge density. Fine particles are repulsive and can be released when double-layer energy dominates, especially when surface charge density is high.

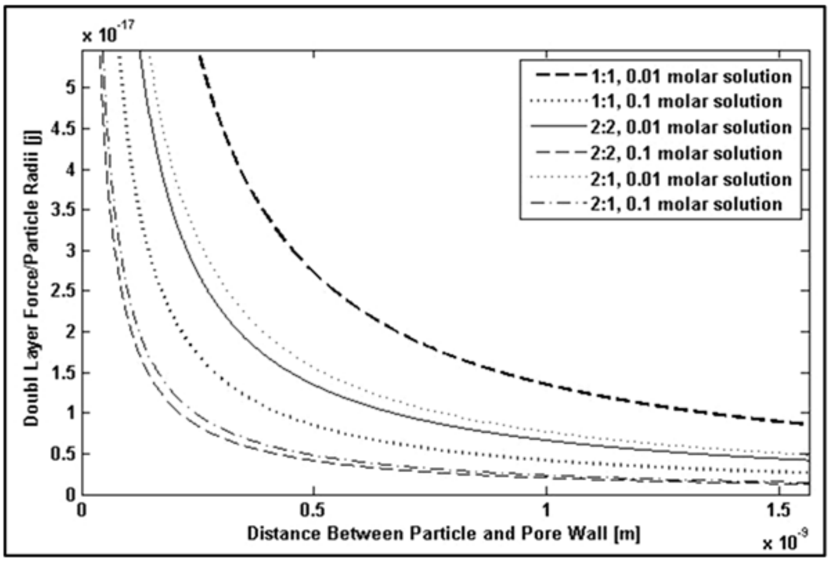

Figure 2.10 Decrease of EDL by the increase of ionic strength (Sourani et al., 2014)

In contrast, when the surface charge density is low, there is a high salt concentration and a dominating of attractive forces. Moreover, since the repulsive forces dominate at intermediate distance values, the distance with the Debye length is comparable. To measure the Ionic strength, Sourani et al. (2014) used a formula:

$$I=\frac{1}{2}\sum cz^2 \tag{2.14}$$

where c and z are the number and valency of ions, respectively.

2.4.2 Hamaker Constant

Hamaker constant is the parameter that measures the strength of van der Waals forces between materials and represents the interaction between two uncharged and nonpolar surfaces in a vacuum (Oshima & Takeda, 2024). The Hamaker constant can be determined by several factors related to surface interaction with material and influenced by their dielectric properties, surface energies, and separation distances. Israelachvili (2011) studied that the Hamaker constant (A_H) can defined as:

$$A_H=\pi^2 C\rho_1\rho_2 \qquad (2.15)$$

Where ρ_1 and ρ_2 are the number of atoms per volume unit, C is the atom pair potential coefficient. Oshima & Takeda (2024) showed that the range of the Hamaker constant is between 10^{-20} and 20^{-19}. J, Israelachvili (2011) mentioned that its range is approximately $(4\text{-}0.4)10^{-19}$ J.

Since the Hamaker constant is not an independent parameter, Muneer et al. (2020) described it as a constant that depends on factors such as particle size, shape, salinity, and surface properties. According to Yang et al. (2022), the Hamaker constant can also change due to ionic strength. The authors explain how the Hamaker parameter depends on salt levels while describing its theoretical mathematical evaluation method. The attraction forces will decrease in systems containing salt, whether it stems from sandstone or limestone structures. Muneer et al. (2022) recorded A_H reduction throughout their pH measurements particularly below a pH value of six. An elevation of solution pH offers better conditions for particle interaction. The strength of inter-particle attraction increases with Higher values of the Hamaker constant and decreases when this value falls. In conditions with high Hamaker constant values particle migration emerges as increasing pH levels decrease attractive forces between particles to improve their mobility.

2.4.3 Zeta Potential

The zeta potential works as an indicator of charge because it demonstrates the decreasing forces that repel particles from each other. Zeta potential functions as a measurement tool that indicates the charge level by showing the differences between inner and outer layers of fines or grains and the way repulsive forces vary. Schramm et al. (1991) presented the calculation method, which depends on ionic strength and pH, and ionic composition levels. The evaluation of zeta potential serves as an excellent method for describing fines migration due to its more convenient measurement compared to surface charge measurement (Muneer et al., 2022; Mansour et al., 2020). The authors state zeta potential serves as an important measure to evaluate electrical double layer (EDL) due its accuracy in approximating surface charges. Zeta potential measurement involved a zeta sizer instrument according to Muneer et al. (2020) based on electrophoretic mobility principles. The research demonstrated that when NaCl concentration decreased, so did the zeta potential value, thus leading to increased Debye length and extended electrical double layer along with increased repulsive forces between sand grains and fines. Laboratory tests showed that the sample zeta potential values stood between -35 and -28 millivolts. The researchers demonstrated that zeta potential challenges can occur when implementing alkaline flooding techniques, although the pH measurement remains at its average level of 7. The analysis of Ali et al. (2022) said zeta potential establishes positive characteristics during acid environments in Figure 2.11. Using kaolinite and quartz samples, Gao et al. (2004) determined that their zeta potentials at pH 7.4 amounted to -43.42 mV and -57.92 mV, respectively. These measurements were explained by the presence of clay particles in porous media and the influence of pH on clay mineralogy. Moreover, the measurements were made using electrophoretic mobility, which revealed that as pH decreased, the zeta potential increased. Muneer et al. (2020) also examined the relationship between zeta potential and pH. Studies showed that zeta potential decreases with increasing pH due to the alkaline system and the presence of OH- ions. This is linked to surface forces, where a negative charge leads to repulsive forces and the release of clay from the rock surface. In summary, zeta potential is an important parameter in DLVO modeling, which can be used to measure charges between layers and show negative signs during clay deposition.

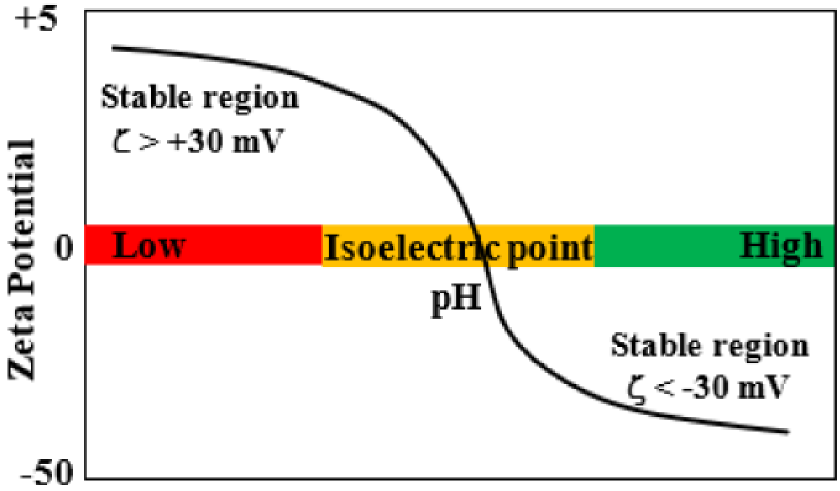

Figure 2.11 Zeta potential changing based on pH (Muneer et al., 2022)

2.5 DLVO Application to Predict Fines Migration

The development of predictive fines migration models requires complete comprehension of how interparticle forces within the DLVO framework respond to changes because these forces dictate fines adhesion and detachment rates. Yang et al. (2022) demonstrated through their study of porous media systems that modeling DLVO forces would enable the observation of system sensitivity to parameters that influence fines release. Salinity showed greater influence on electrostatic forces than it did on van der Waals and Born repulsion forces based on the authors' investigation. The model indicates that zeta potential stands as the main controlling element between salinity changes and EDL expansion. The electrostatic repulsive forces become weaker because reducing zeta potential occurs within high-salinity conditions. Elimelech et al. (2013) state that van der Waals attraction and Born repulsive forces are less sensitive to salinity since ionic strength does not impact the Hamaker constant. For instance, Figure 2.12 illustrates the effect of salinity on DLVO forces, showing a decrease in EDL forces as the salt concentration in brine increases. However, the double layer force exhibits a nonmonotonic trend near the primary minimum, initially increasing and then decreasing with salinity. As a result, the total DLVO force first decreases and then increases at the primary minimum.

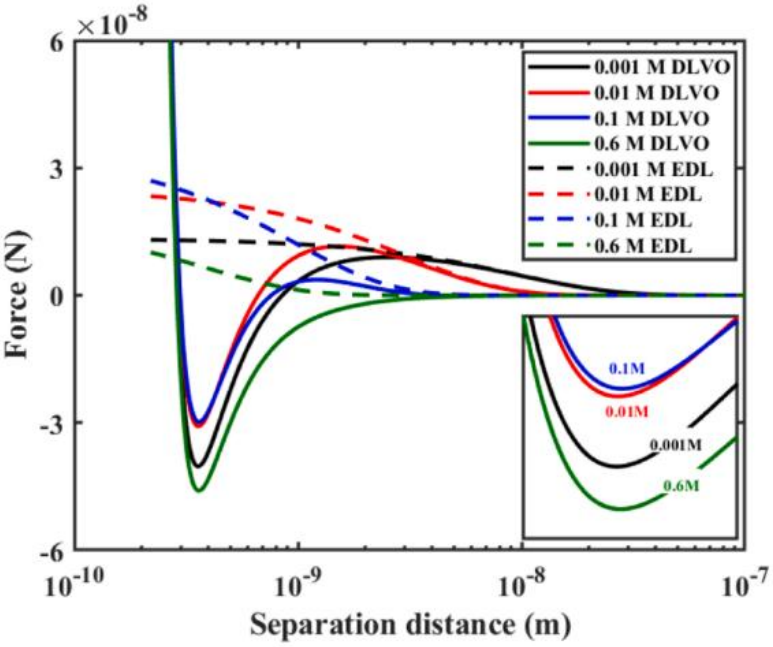

Figure 2.12 Effect of salinity on DLVO forces (Yang et al., 2022)

Another method to prevent clay particle migration is the use of nanoparticles, as they can alter the surface properties of rock by adsorbing onto it. During alkaline flooding in the reservoir, DLVO modeling can predict the CSC and critical pH values based on the nanoparticles used to enhance attractive forces. Arab and Pourafshary (2013) studied the surface charge of a damaged rock system and how it could be modified using nanoparticles before low-salinity water injection. However, Giraldo et al. (2021) argued that, to understand how fines interact with nanoparticles or sand, a charge balance analysis is required (Figure 2.13). It is important to note that kaolinite has a negative charge, while alumina nanoparticles have a positive charge, leading to stronger attraction between particles. On the other hand, magnetite or silica nanoparticles are negatively charged, which results in increased repulsion between the clay particles and the nanoparticles.

Despite this charge balance analysis, Muneer et al. (2020) noted that silica dioxide, magnesia, and aluminum oxides can block clay minerals and prevent their release. For example, Assef et al. (2014) and Mansour et al. (2020) proposed enhanced oil recovery methods by adding MgO to the injection fluid. However, there is a possibility that the solution suggested by Assef et al. (2014), which involves using MgO nanoparticles before water injection, may lead to further formation damage. Consequently, an additional investigations are needed, since they used low-salinity water.

On the other hand, Mansour et al. (2020) compared the use of nanofluids with SiO2 and MgO and concluded that attaching clay particles to sand grains was more effective with MgO than with silica oxide. However, it should be noted that Mansour et al. (2020) focused on the effect of fluid flow rate on fines migration and did not specify the type of water used for injection. Additionally, Agi et al. (2023) also studied nanoparticles like SiO2 and hypothesized that using these nanoparticles could prevent fines release when low-salinity water is used. Overall, several studies have explored the effect of fluid injection rate and nanoparticle composition on fines migration. These studies suggest that nanoparticles have a positive effect on preventing fines migration, though there may still be a risk of further formation damage.

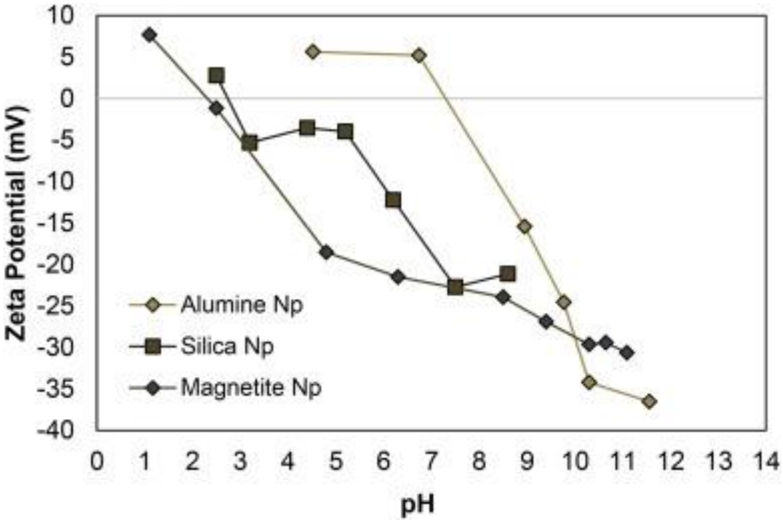

Figure 2.13 Zeta potential of NPs (Giraldo et al., 2021)

2.6 The Effect of pH on DLVO Forces

Reductions in both ionic strength and changes to ionic composition contribute to formation damage caused by fines migration and permeability reduction. The zeta potential reflects the charge on particular materials thus maintaining close links with both surface charges and fluid pH values. This relationship was studied by Yang et al. (2022) along with Schramm et al. (1991) and Barnaji et al. (2016) through their research using solutions containing NaCl at different pH levels. Increasing the pH of the salt solution resulted in increased negative zeta potential values according to their findings. The surface charge together with the EDL force experiences changes through the combined influences of pH and ionic characteristics. Adding more salt and dissolved cations to the solution reduces the effectiveness of electric double-layer forces at the solution surface. Rock surfaces consisting of sandstone along with limestone and dolomite surface demonstrate negative charges within NaCl solutions with neutral pH but they show positive charge characteristics in high pH solutions according to Schramm et al. (1991).

Additionally, as shown in Figure 2.14, the effect of varying pH on the energy barrier of the material can explain these changes (Muneer et al., 2022). Cationic charges within the solution decreased as the pH value increased under salinity maintenance conditions. Research showed that at 0.2 M saline, the electrostatic force potential dropped from -5 to -31 between pH 0.2 and pH 12.

The pH effects on the material may show variations between multiple sections because their charge values differ from each other. The researchers described this variability through their investigation of kaolinite surfaces (Yang et al. 2022). The edge surface of kaolinite connects two hydrogen atoms (OH- and H+) with opposing charges, whereas its face section shows a steady negative surface potential. Assef et al. (2014) explained that the phenomenon occurs when clay particles and sand grains interact through colloidal forces. Water containing low levels of salinity and freshwater shows heightened repulsive forces since their water salinity stays below the CSC. The authors state that colloidal forces depend on ionic strength and pH, but the edge surface of kaolinite reacts more strongly to changes in pH than the face surface does.

Rock surfaces that have positive energy interactions with clay particles result in stronger repulsion forces than attractive forces that control fine particle movement. Research has investigated oil-recovery enhancement methods by minimizing the strong repulsive interactions between fine elements when using low salinity water for injection. According to Assef et al. (2014), the force attraction of oil to rock may create barriers that stop oil flow. According to Nasralla et al. (2011), low salinity water consists of a lower ionic strength than rock materials, thus, it modifies the rock surface charge into a negative state. A higher pH value in low salinity water boosts the electrical double layer, which draws crude oil toward the rock surface because of improved permeability.

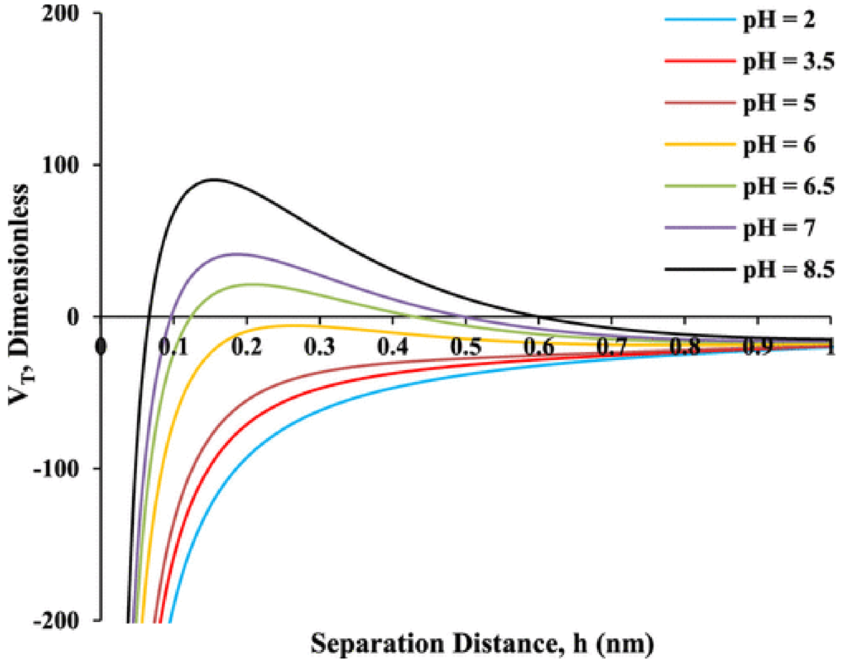

Figure 2.14 pH sensitivity on DLVO interactions (Muneer, et al. 2023)

When the energy interaction between the rock surface and clay particles is positive, the repulsive forces controlling fine particle movement are greater than the attractive forces. Despite the high repulsive forces between fine particles during low salinity water injection, some studies have explored enhanced oil recovery methods by reducing the attractive forces.

Assef et al. (2014) suggested that the attractive forces between oil and rock can trap the oil, preventing it from moving. Nasralla et al. (2011) explained that the ionic strength of low salinity water is lower compared to that of the rock, which can alter the surface charge of the rock, making it more negative. The electrical double layer increases as the pH of the low salinity water rises, causing crude oil to adhere to the rock surface due to wettability.

However, in their experiment, Barnaji et al. (2016) used several types of water with different pH levels, including seawater with pH = 7.98, artificial seawater with lower salinity and pH = 6.95, and the same water with pH = 12. Their studies revealed that fines migration was minimal in high salinity water with the lowest pH, but migration increased as the pH rose. Additionally, connate water was present, which led to oil trapping and sweeping. Enhanced oil recovery may occur during low salinity water injection in the absence of connate water.

3. METHODOLOGY

3.1. Introduction

Formation damage in oil and gas reservoirs is related to hydrocarbon production. It happens because of negative fluid-rock particle interactions and the fluid-induced changes caused by fluid movement. Drilling mud and injection fluids used in enhanced oil recovery can cause common formation damage. In addition, drilling mud may change reservoir fluid properties while injection fluids also squeeze solid rock particles (Assef et al., 2014; Barnaji et al., 2016; Muneer et al., 2022). The pore blockage reduces permeability, and oil recovery is undesirable.

A key challenge of the oil recovery operation is fines migration, a result of the detachment of fine particles from the reservoir rock and their migration into the porous media. However, this process is affected by various fluid and rock parameters, including brine salinity, pH, chemical composition, and flow rate (Muneer et al., 2023). For example, the balance between repulsive and attractive forces, depending on the brine injection rate, and how hydrodynamic forces vary and influence fines detachment, are also dependent upon brine injection flow rate. From an electrostatic point of view, the risk of permeability decline with saltwater injection is less than with freshwater injection. Thus, the particle stability is strengthened because the electric double layer is compressed as the charge density of the fines, rock, and brine system is high. However, in all cases, the stability is compromised by electrostatic forces if the brine salinity falls below the CSC, or if the pH changes during alkaline water injection, or as a result of dynamic forces that tend to increase with increasing flow rate.

Since each property of a reservoir rock influences the initiation of fines migration and formation damage, understanding the threshold values at which fines begin to detach is critical. Reservoir rock properties such as porosity, permeability, and mineral composition play a role in determining these critical values. For example, rocks with high concentrations of clay or specific minerals may be more sensitive to fine detachment. This raises the question: what is the critical pH value, and how does pH affect formation damage under different conditions?

DLVO modeling provides a fundamental framework for understanding the colloidal system and its stability, helping to predict the critical pH by modeling the electrostatic forces between system particles. According to DLVO theory, particle repulsion is a key factor in the instability of the colloidal system. This repulsion leads to the expansion of the electric double layer surrounding charged particles. Another force that contributes to colloidal stability is attraction, also known as Van der Waals forces. These forces were analyzed to determine the critical pH values, with fine migration occurring at the point where the net interaction between these forces becomes positive.

3.2. Material and Methods

This work includes both modeling and experimental studies, where core flooding experiments with NaCl brine at varying pH levels were conducted to model surface force interactions and predict the critical pH value of the injection fluid.

3.2.1. Measurement of Parameters to Model Fines Migration by DLVO

The DLVO theory explains fluid-rock interactions and their behavior during various water injection processes at different pH levels. The primary goal of applying DLVO modeling in this study is to determine the critical pH at which fines migration begins in Berea sandstone samples, under constant injection water salinity and constant flow rate. This requires calculating the forces influencing fines migration in reservoirs containing crude oil, along with the parameters affecting these forces. Key parameters such as pH, ionic strength, brine salinity, fines particle size, and both measured and modeled zeta potential are used to evaluate surface forces. These forces are then computed to predict the critical pH values under varying salinity conditions.

To determine the attractive and repulsive forces within the brine-sand-fines system, the average size of the fines was measured using scanning electron microscopy, and the zeta potentials of the sand particles were measured using a Zetasizer and subsequently modeled. Each brine sample's salinity and pH were taken into account very carefully. Van der Waals, electric double-layer forces, and Born repulsion forces were calculated using Equations 2.3, 2.6, and 2.7, respectively (Gregory, 1981; Sourani et al., 2014; Muneer et al., 2020).

After calculating each repulsive and attractive force, they were quantified using Equation 2.1 (Trefalt & Borkovec, 2014; Muneer et al., 2020; Khilar and Fogler, 1998; and Mansour et al., 2020), and the DLVO model was developed. Several constant parameters are shown in Table 3.1.

Table 3.1 Constant parameters that are used for the DLVO application in our study

Parameter	**Symbol**	**Value**
Fluid Temperature	T	297.15 K
Hamaker constant	A_H	3×10^{-21} J
Boltzmann constant	K_B	1.38×10^{-23} JK^{-1}

The dielectric constant of water	ε_m	80
Permittivity of vacuum	ε_o	8.85×10^{-12} $C^2J^{-1}m^{-1}$
Electron charge	e	1.6×10^{-19} C
Avogadro’s Number	N_A	6.02×10^{23} $mole^{-1}$
Atomic collision diameter	σ	5×10^{-10} m
Effective electrostatic force	F_e	3.07×10^{-11} kg m/sec^2
Brine viscosity	μ	0.001121 kg/m sec
Pore radius	r_p	5×10^{-5} m
Kaolinite density	ρ_f	2650 kg/m^3
Brine density	ρ	970 kg/m^3

3.2.2. Brine Preparation

The brine salinity was selected to exceed the CSC, as fines migration cannot occur in highly saline environments. Therefore, injection brine salinities of 0.2 M NaCl and 0.25 M NaCl were chosen. Brines with different pH values, ranging from 6.5 to 11, were prepared at each salinity level (0.2 M and 0.25 M NaCl) to measure the critical pH. Reagent-grade NaCl (Sigma Aldrich) was dissolved in distilled water using a magnetic stirrer to prepare the brines. During measuring a pH with a digital pH meter, a systematic approach is used to make sure it is accurate and reliable. The pH meter was first calibrated against standard buffer solutions (pH 4.0, 7.0, 10.0), which were rinsed off and thoroughly rinsed with distilled water at each calibration to avoid contamination with cross. The samples were carefully stirred at room temperature, and pH measurements were taken once the readings stabilized.

For the experimental phase, Berea sandstone core samples were saturated with formation water with a salinity of 76,960 ppm. The compositions of NaCl brine and formation water are presented in Table 3.2. The composition of the NaCl brine and formation water was adjusted by adding NaOH, and samples with pH values ranging from 6.5 to 11 were prepared at each salinity level.

Table 3.2 Composition of NaCl brine and formation water.

Ions	Formation water (ppm)	0.2 M NaCl brine (ppm)
Na+	23427	4595
Ca+	4450	0
Mg+	1302	0

Cl-	47781	7092
Total	76960	11687

3.2.3. Rock Preparation

The critical pH for the sandstone reservoir was determined from two Upper Berea Sandstone outcrop samples. Grain size, particle size distribution, and chemical composition of cores were established, and then cores were selected and characterized. The samples were on average 7.5 cm in length and 3.8 cm in diameter. The morphology and grain size of the sandstone were assessed using Scanning Electron Microscopy with Energy Dispersive Spectroscopy (SEM-EDS), while the mineralogical composition, as well as quantification of the amount of key minerals responsible for controlling the surface charge behaviors, were determined by X-ray Diffraction (XRD) measurements. A combination of SEM and XRD data provides a complete understanding of the physical and chemical properties of sandstone that are necessary for accurate modeling of DLVO. XRD mineralogic analysis of a sample indicated that the sample is made up of quartz, with trace amounts released magnesium oxide (MgO), iron Fe2O3), aluminium silicate (Al2SiO5), and aluminium oxide (Al2O3) as seen in Table 3.3. SEM was used to better understand the rock’s composition and physical and mechanical properties. Figure 3.1 shows that, as shown in Figure 3.1, the Berea outcrop sample indicated that in the highest concentration in the Berea outcrop sample of elements was silicon.

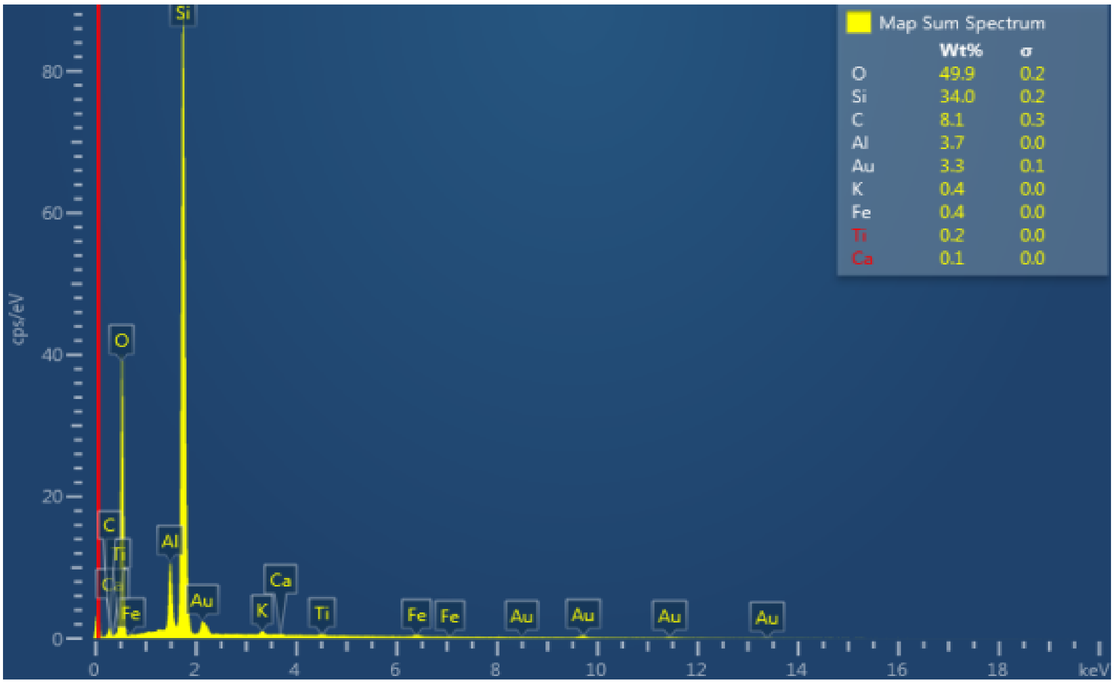

Figure 3.1 Elemental composition of sandstone sample determined by SEM-EDS

Table 3.3 Mineralogy of sandstone sample determined by XRD

Chemical composition	Formula	Weight (%)
Quartz	SiO_2	87.14
Kaolinite	$Al_2Si_2O_5(OH)_4$	6.41
Aluminum oxide	Al_2O_3	3.97
Magnesium oxide	MgO	0.81
Iron oxide	Fe_2O_3	1.67

First, Berea Sandstone samples were cut and dried in an oven, and their dry weights were recorded. Distilled water was then used to saturate the samples using a Vinci manual saturator. After saturation, the wet weights of the samples were measured again to determine porosity, which ranged from 0.192 to 0.194, and liquid permeability, estimated to be about 350-400 mD.

3.2.4 Zeta Potential Determination

Zeta potential measurements are a useful method for studying the behavior of colloidal particles in liquids. Using a core-crushing apparatus, a Berea sandstone core sample was crushed, and the resulting fine powder was sieved through a 40 μm sieve to measure the sand-brine zeta potential. To ensure a representative sandstone sample and remove contaminants, the sand powder underwent multiple rounds of thorough cleaning and washing. The cleaning process involved using n-hexane, acetone, and distilled water. After drying the samples in an oven at 60 °C for one day, they were rinsed with 0.5 M hydrochloric acid and further cleaned with solutions of 0.2 M and 0.25 M sodium chloride, adjusted with sodium hydroxide, until the rinsate pH matched that of the brine (as detailed in Table 3.1).

Following 24 hours of equilibrium exposure, zeta potentials were evaluated using Malvern Zetasizer equipment to confirm that the brine-to-sand particle ratio was appropriate (Figure 3.2). The measured zeta potentials for the sand-brine systems were incorporated into DLVO modeling, and pH values were assessed for all samples.

Figure 3.2 Malvern Zetasizer equipment used for measuring the zeta potential of sand-brine systems.

Although the experimental method of measuring zeta potential using a zeta sizer is widely applied, it has certain limitations. This method can be time-consuming and resource-intensive, and it is challenging to scale for subsurface conditions across a broad range of variables. Thus, there is a necessity of alternative approaches that are both efficient and reliable.

In order to have a more in-depth look into zeta potential, another predictive model based on the XGBoost machine learning technique was developed. eXtreme Gradient Boosting, or XGBoost, is a machine learning algorithm that combines boosting techniques with decision trees. For predicting zeta potential, XGBoost offers some key features, such as regularization and the ability to handle missing values, that make it well-suited for. Robustness makes it possible for this algorithm to work with datasets in the real world that are possibly even noisy or constrained, and for these regression problems.

Analysis of the prediction of the zeta potential using XGBoost took four steps, which were data collection, data preprocessing, training the model, and evaluation. A dataset was created from 173 data points from academic papers based on zeta potential that was experimentally determined or modeled. pH, ion type, temperature, ionic strength, and medium were considered as parameters. The variation of temperatures was in the range of 15 to 145 °C, and the ionic strength ranged from 0 to 29,220 ppm NaCl and 0 to 20,000 ppm KCl. To account for the effects of different surfaces on zeta potential behavior, the dataset included various porous media such as Berea sandstone, gray sandstone, Buff sand, clay sand, Bandera, Parker, glass beads, kaolinite, and coal fines. Brine pH values ranged from 1 to 12.

Data preparation for machine learning involved normalizing all continuous features, such as pH, salinity, temperature, and ionic strength, to a range between zero and one. This normalization step prevented large-scale features, like salinity, from overshadowing smaller-scale features, such as pH. Categorical variables, like the type of porous medium, were converted to binary values to align with available models and ensure interpretability.

The finalized dataset was split into three subsets: 70% for training, 15% for validation, and 15% for evaluating model performance. Stratified sampling was applied to ensure uniform distribution of features, including pH, salinity, temperature, and porous medium type, across all subsets.

Exploratory data analysis was performed to identify trends and relationships between features. Feature distributions, variability, and correlations with zeta potential were examined. Histograms were used to analyze the distributions of continuous features, such as pH, salinity, temperature, and ionic strength. Most features were approximately evenly distributed, though some, like salinity, showed slight skewness. This analysis informed the normalization step, ensuring uniform scaling of the raw data.

As shown in Figure 3.3 and Figure 3.4, the dataset's zeta potential values ranged from positive to negative, with negative values indicating surface repulsion and positive values indicating attraction. The pH values in the dataset covered a range from acidic to alkaline, capturing both repulsive and attractive surface interactions. This diversity in the dataset was essential for building a robust model capable of predicting zeta potential across a wide range of ionic strengths and chemical environments.

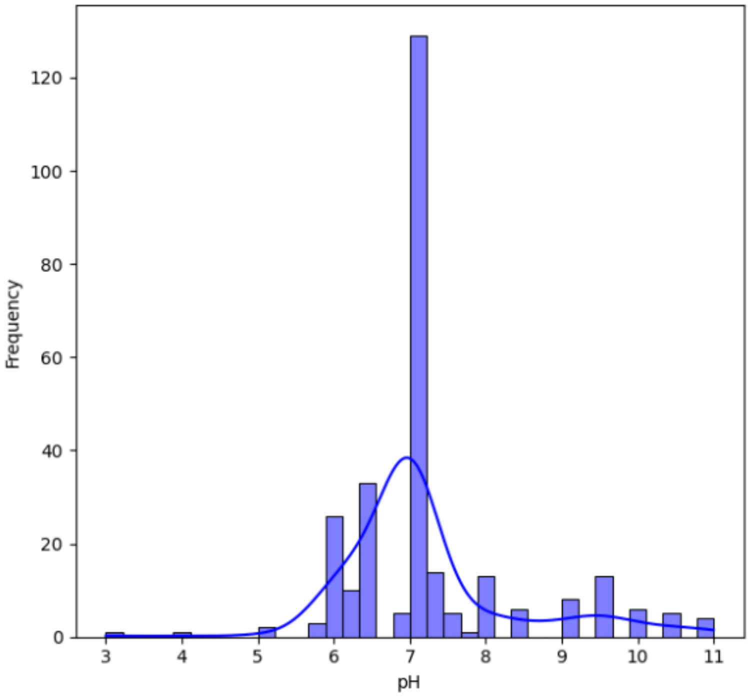

Figure 3.3 Distribution of the pH over the collected data set

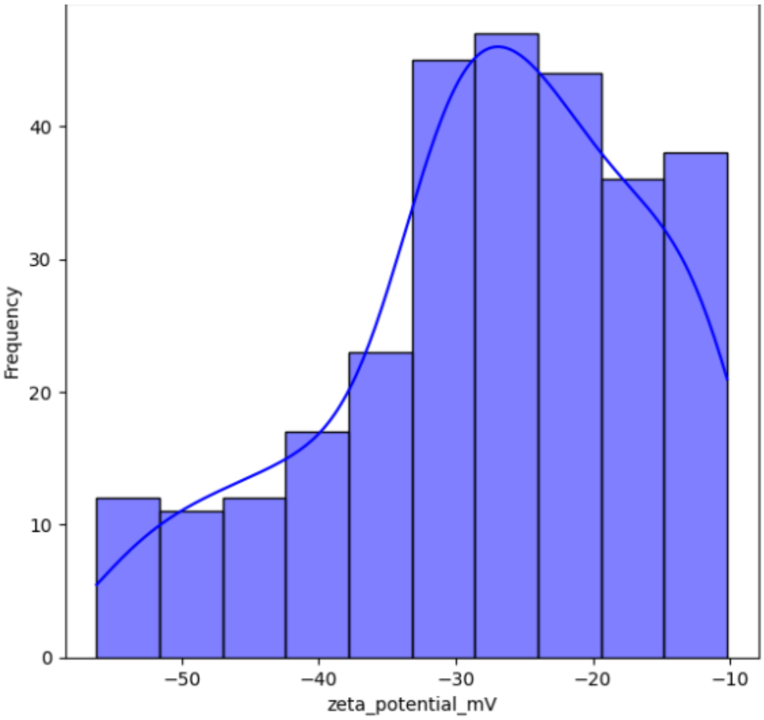

Figure 3.4 Distribution of the zeta potential over the collected data set

The measured data were tested for consistency and then used as input for modeling, ensuring complete coverage of surface charge behavior. The model was then improved and better applicable for zeta potential prediction under numerous conditions.

Input variables were evaluated on the basis of a feature importance analysis to evaluate the relative significance. First, this initial step served to identify the features which most likely to influence the potential prediction, thus serving as a guide for the model-building process.

The exploratory data analysis definitely showed the dataset to be valid and representative, which served as a clue that the dataset is well-suited for machine learning. As a result of this groundwork, it was essential to have robust predictive models.

However, I made an initial prediction by using the same XGBoost to train the dataset. A decision tree was constructed based on similarity score of residuals, i.e. difference of observed and their predicted values. We also computed the output values using the residuals generated in the residuals of the previous trees and these generated new residuals for the subsequent trees. The residuals continued until they stopped decreasing.

The squared error was used as a function that minimized the difference between the predicted and actual values. Therefore, several parameters had been fine tuned to balance between the complexity of the model and its generalizability. For example, a learning rate of 0.1, number of boosting rounds of 100 and maximum tree depth 6 was used. The model was also trained on standardized data in order to contribute equal amount from all parameters.

Modeling was carried out using Google Colab with the XGBoost library. The primary objective was to evaluate the accuracy of predicting zeta potential using machine learning, reducing reliance on laboratory experiments. This approach aimed to optimize the zeta potential prediction process and expand the range of observations related to fines migration. To validate the model's accuracy, the simulated results were compared with experimental data.

3.2.5 Core Flooding for Low-Rate Fluid Flow

A series of coreflood tests using NaCl brine was conducted to measure critical pH. Each test was performed at room temperature (24 °C), maintaining a back pressure of 260 psi and a confining pressure of 1000 psi. The injection sequence for the core flooding test is detailed in Table 3.3. As the salinity of the system was reduced from 77,000 ppm to 11,688 ppm (0.2 M NaCl) and 14,610 ppm (0.25 M NaCl), soaking time between injections was necessary to establish surface force equilibrium. For each test, 2 pore volumes (PV) of the specified NaCl brine were injected at a rate of 0.2 cc/min, followed by a 24-hour soaking period. After soaking, brine with the same salinity but an increased pH was injected. The coreflood sequence is summarized in Figure 3.5, and the same methodology was applied using 0.25 M NaCl brine. The low injection rate of 0.2 cc/min was chosen to minimize the effect of hydrodynamic forces on fines migration. The pH was systematically increased from 6.5 to 11 in increments of one.

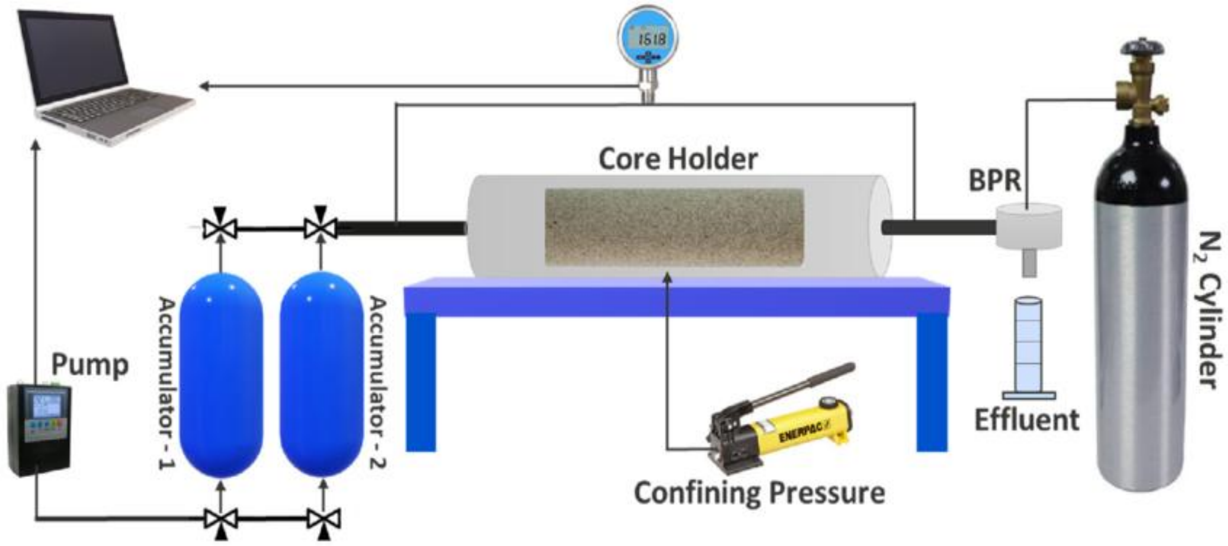

Figure 3.5 Graphical representation of coreflood system

3.2.6 DLVO Model considering Hydrodynamic Forces

To predict critical pH for fines migration initiation, tests at both low and high flow rates were conducted to consider a complex interaction between electrostatic interaction and hydrodynamic forces within the porous media. When the flow rate is low, there is a negligible effect of forces applied on fines particles by fluid movement, allowing us to understand better the surface charge effect on fines release. However, during fluid injection at high flow rates, the increased shear stress applied by the fluid flow on the rock surface becomes the primary factor influencing particle migration. Consequently, there is a significant rise in hydrodynamic forces, which, as a result, outweighs the electrochemical forces, leading to particle detachment. Overall, the evaluation of these flow ranges may help to predict accurately the critical pH at different reservoir conditions.

Since fine detachment during the high flow rate can be affected by several forces such as hydrodynamic or drag force (Fd), lift force (Fl), electrostatic force (Fe), and gravity force (Fg), these forces were found. The electrostatic force was found by using separation distance and taking the derivative between total energy values. Hydrodynamic forces have a significant role during the injection with a high rate because of flow rate fines, detachment may occur earlier than at critical pH.

To estimate these forces, there was a need to measure additional parameters, which are shown in Table 3.1. There were used the same procedures for brine preparation. Brine viscosity and density were measured by Anton Paar’s viscosimeter. Moreover, this table shows the effective electrostatic force, pore radius, and density of fine particles. The pore and particle radius were measured by a scanning electron microscope.

3.2.7 Coreflooding Experiment at High Flow Rate

To evaluate the effect of surface forces on fines migration, sensitivity analyses on fluid flow rate in oil reservoirs are used. Since the range of flow rate of the liquid is necessary, as well as the salinity, and can affect the detachment of clay and the subsequent change in permeability, it is possible to prevent fine migration by controlling the fluid flow rate.

The test began with an injection of 3 PV of brine at a rate of 0.2 cc/min, after which a soaking period was given to ensure sufficient contact between the sand, fine, and injection brine. Then, the same 0.25 M NaCl brine was injected, and the injection rate gradually increased with each 3 PV injection. 3 PV was chosen to see any pressure change in the system. Due to the potential for fine migration, pressure drop values were recorded at each step. The test was carried out to determine the experimental value of the critical flow rate at a higher CSC salinity and lower critical pH. The injection rates are listed in Table 3.4.

Table 3.4 The procedure for coreflooding with increased rates

No.	Design
1	0.25 M NaCl, pH=8 injection at 0.2 cc/min → 1 cc/min → 2 cc/min → 3 cc/min → 4 cc/min → 5 cc/min

3.2.8. Effluent Analysis

At the end of each flooding, pressure difference data and effluents were collected at various pH levels of the injected fluid. UV-VIS spectroscopy was employed to analyze the effluent, a method that determines the concentration of compounds in a sample by measuring ultraviolet absorption. By examining the data, the critical pH level and the presence of fine particles can be compared with the results of the DLVO theory, which is supported by higher absorption at specific wavelengths.

4. RESULTS

4.1 Modeling of Fines Migration by DLVO at a Low Rate

4.1.1 Zeta Potential Measuring and Modeling

Zeta potentials for 0.2 M NaCl and 0.25 M NaCl were determined after cleaning the sand particles and dispersing them in brine using a magnetic stirrer and ultrasonic homogenizer. The zeta values for these concentrations are shown in In other words, the developed machine learning XGBoost approach was used to model the values for other types of brine.

Experimental values for 0.2 M NaCl and 0.25 M NaCl were used to validate the accuracy of the model's output parameters. **Ошибка! Неверная ссылка закладки.** also presents the differences between experimental and modeled zeta values. The decrease of the zeta potential with increasing pH of the brine may be attributed to the presence of additional hydroxide ions in the solution. Furthermore, temperature has an effect on zeta potential at various pH values, thus, the experiments were performed at room temperature to keep other factors in play to a minimum in the output values.

Table 4.1 and Table 4. 2, respectively. In other words, the developed machine learning XGBoost approach was used to model the values for other types of brine.

Experimental values for 0.2 M NaCl and 0.25 M NaCl were used to validate the accuracy of the model's output parameters. **Ошибка! Неверная ссылка закладки.** also presents the differences between experimental and modeled zeta values. The decrease of the zeta potential with increasing pH of the brine may be attributed to the presence of additional hydroxide ions in the solution. Furthermore, temperature has an effect on zeta potential at various pH values, thus, the experiments were performed at room temperature to keep other factors in play to a minimum in the output values.

Table 4.1 Comparison of experimental and modeled zeta potential values for 0.2 M NaCl.

Medium and Ionic strength	pH	Z (experiment)	Z (model)
0.2 M NaCl	6	-18.2	-17.06
	7	-20.4	-20.69
	8	-23.7	-21.01
	9	-25.8	-22.6
	10	-27.5	-26.04
	11	-28.9	-29.81
	12	-31	-30.41

Table 4. 2 Measured zeta potential values for 0.25 M NaCl.

Medium and Ionic strength	pH	Z (experiment)	Z (model)
0.25 M NaCl	6.5		-16.5
	7.5		-16.97
	8.5	-17.42	-17.38
	9	-18.97	-18.31
	9.5		-23.6
	10	-27.13	-26.86
	10.5		-27.11
	11	-28.43	-28.81

For the brines with a salinity of 0.25 M NaCl, the properties of the samples and the modeled zeta values are shown in Table 4. 2. Similarly, the zeta potential decreases with an increase in pH.

To validate the effectiveness of the zeta potential prediction model for different ionic strengths, additional values were modeled, as shown in Table 4.3 and Figure 4.1. The model validation demonstrated an accuracy of 92%. A decrease in brine salinity leads to a reduction in zeta potential, similar to the effect of increasing pH toward basic conditions. These changes can result in the expansion of electric double layers and an increase in repulsive forces, which contribute to the migration of fine particles.

Table 4.3 Modeled zeta potential values for varying ionic strengths.

Medium and ionic strength	pH	Z
0.1 M NaCl	6	-21.03
	7	-22.02
	8	-22.63
	9	-24.15
	10	-27.39
	11	-30.32
0.2 M NaCl	6	-17.06
	7	-20.69
	8	-21.01
	9	-22.6
	10	-26.04
	11	-29.81
0.3 M NaCl	6	-15.45
	7	-16.74
	8	-17.67
	9	-18.26
	10	-19.25

	11	-26.73

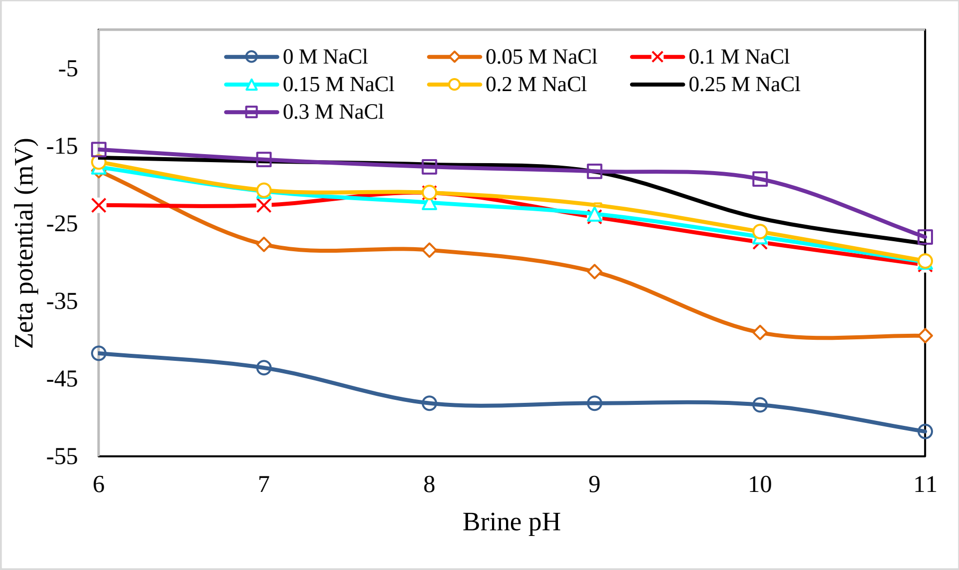

Figure 4.1 Sensitivity of modeled zeta potential to the pH and salinity of brines.

4.1.2 DLVO Modeling to predict Critical pH for the Initiation of Fines Migration

For DLVO modeling, NaCl brines with pH levels ranging from 6 to 11 were used. Surface forces between fines and sand grains were estimated based on observed zeta potentials under various pH conditions and brine ionic strengths. The total interaction energy of each system was determined using DLVO modeling, as illustrated in Figure 4.2 and Table 4.4. The total interaction energy represents the sum of the attractive and repulsive potentials in the system.

The critical pH point was identified as the threshold where the attractive forces between fine particles in a sandstone sample and the injected brine are no longer sufficient to counteract the repulsive forces. This imbalance causes particle separation and subsequent migration.

For 0.25 M NaCl injection brine, sand grains and fines were surrounded by compacted EDL at pH values between 6.5 and 9.5. Under these conditions, the attractive forces outweighed the repulsive forces, resulting in negative total interaction energy, which indicates that fines migration does not occur. However, as the pH increased beyond 10, the total interaction energy became positive, reflecting stronger repulsive forces. This shift can be attributed to the increased pH, which enhances the EDL forces between sand and fines. EDL expansion preserves particle separation, thereby increasing repulsive forces.

Salinity also influences EDL expansion. At 0.25 M NaCl, the ionic strength prevents significant EDL expansion at low pH due to the higher ion concentration in the brine.

Consequently, the critical pH for fines migration was observed to be 10, as the increased hydroxide ion (OH^-) concentration at higher pH levels outweighs the effects of ionic strength.

A critical pH of 8 was obtained by testing with 0.2 M NaCl, which has been identified as the CSC for fines migration initiation (Muneer et al., 2022). Total interaction energy started to be positive at pH 7 for 0.1 M NaCl brine salinity and negative at pH 7 for 0.3 M NaCl brine salinity using modeled zeta potential values. This suggests that zeta potential depends on ionic strength and is reduced by reducing pH, and thus salinity plays a role in electrostatic interactions.

Because of the reduced ionic strength at low salinities, EDL expansion is significant which consequently results in higher separation of particles. Nevertheless, at high salinities, the increase of ion concentration decreases the dependence of the system on pH. Therefore, expansion of EDL is less pronounced for salinities of 0.2 M NaCl and greater, even at high pH.

Furthermore, DLVO modeling revealed that the Debye length, which varies with ionic strength, contributes to the expansion of repulsive forces. As the EDL strengthens, the Debye length increases, further influencing the system's electrostatic interactions.

Debye length values for both brines are shown in Table 4.4. Moreover, the table shows the maximum values of total interaction energy for each pH of 0.2 and 0.25 M NaCl injected brines to see its dependence on pH.

Table 4.4 The values of Debye length and maximum total energy for injected brines

pH	Salinity (M)	Debye length (nm)	Total interaction energy	The total interaction energy barrier
6.5	0.2	0.685	-14	-
7.5			-13.9	-
8.5			0.13	0.13
9			0.13	0.13
9.5			0.61	0.61
10			2.63	2.63
10.5			4.14	4.14
11			4.34	4.34
6.5	0.25	0.613	-14	-
7.5			-14	-
8.5			-13.9	-
9			-13.9	-
9.5			-13.9	-
10			3.96	3.96
10.5			18	18
11			19.1	19.1

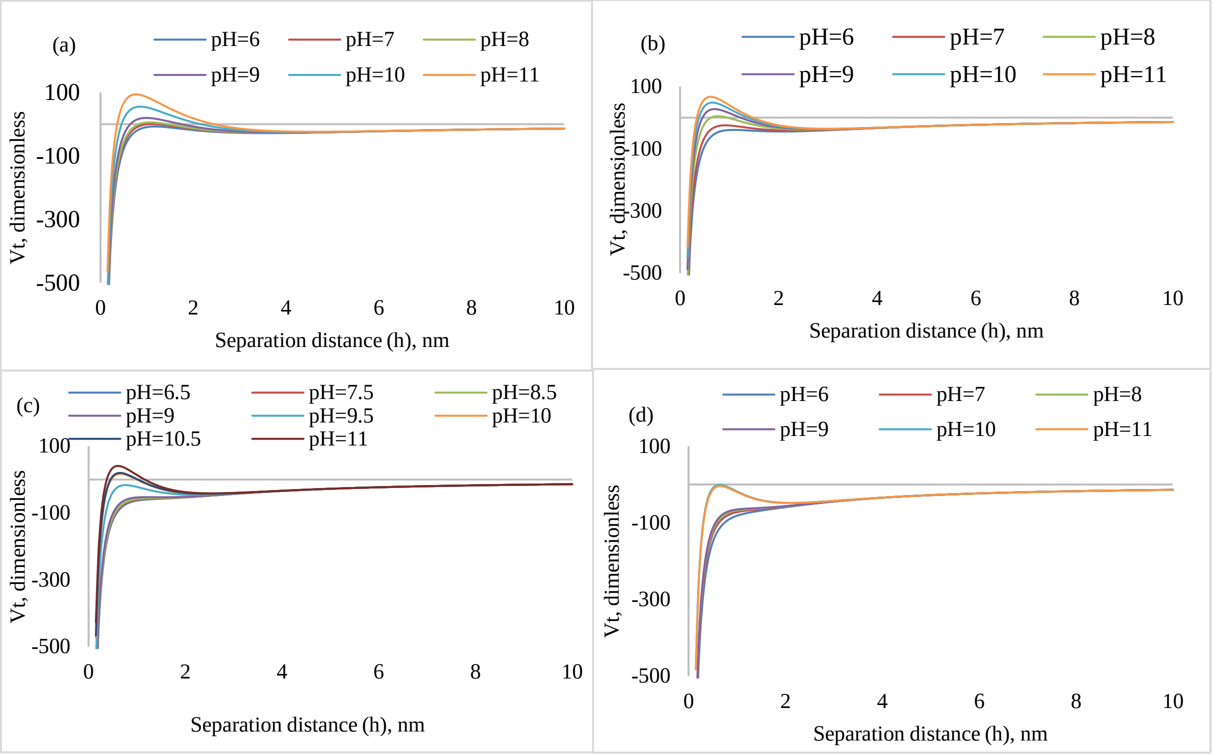

Figure 4.2 Prediction of critical pH using DLVO modeling for (a) 0.1 M NaCl (b) 0.2 M NaCl (c) 0.25 M NaCl, and (d) 0.3 M NaCl

Table 4.5 Modeled critical pH values for NaCl injected brines

Brine salinity	0.1	0.2	0.25	0.3
Critical pH	7	8	10	11

In general, the DLVO model is used to predict critical values of injection brine parameters, such as critical salt concentration and pH, to determine the onset of fine particle migration. The results for ionic strengths of 0.2 and 0.25 M NaCl showed critical pH values of 8 and 10, respectively, indicating that each type of brine has a distinct critical pH value.

4.1.3. Experimental Validation of Fines Migration Initiation at Low Rates

Several factors, such as brine salinity, temperature, and rock composition, influence the critical pH. In this study, the temperature was set to room temperature to avoid any negative effects on the critical pH value, as temperature changes increase the kinetic energy of the system. To simulate reservoir conditions, coreflood experiments were conducted using rock samples. Upper Berea sandstone was selected as the reservoir rock, and mineralogical analysis confirmed that clay particles could act as fines.

To evaluate the effect of salinity on tests involving different pH injections, two coreflood tests were conducted at a low flow rate on Upper Berea sandstones saturated with formation water at 77,000 ppm. A coreflooding system was employed to monitor pressure changes within the core during brine injection, as pressure changes are a significant factor in dislocating fines and influencing their migration. The tests were conducted at a low flow rate to minimize the impact of additional hydrodynamic forces.

During each test, 2 PV of eight brines with varying pH levels were injected into the core samples at a flow rate of 0.2 cc/min. After the injection of the first 2 PVs, a 24-hour soaking period was applied to allow the repulsive and attractive forces to stabilize. This step was necessary due to the reduced system salinity, which declined by 6.5 wt%. Once the system salinity stabilized, brine with the same salinity of 0.2 M NaCl was injected sequentially, 2 PV at a time, to observe the onset of fines release.

As shown in Figure 4.3 and Figure 4.4, no change in pressure drop was observed during the injection of brines with pH levels of 6.5 and 7.5. Minor changes in pressure drop occurred after injecting brine with a pH of 8.5, while significant pressure changes were recorded at pH 9 and above. This indicates that attractive forces dominate over repulsive forces during the injection of brine with a pH below 9.

The second coreflood test followed the same procedure. However, with a brine salinity of 0.25 M NaCl, pressure changes were observed at pH 10 due to the increased salinity. The elevated pressure drop during the injection of brine at pH 10 suggests the release of fines from the sand core surface, driven by the properties of the injected fluid.

These experiments demonstrate that the critical pH value is influenced by salinity, with higher brine salinity resulting in a higher critical pH range. In both tests, fines migration was observed as the pH increased, destabilizing clay particles in the rock samples and causing their migration. The migrated particles likely blocked some pores within the core, leading to formation damage.

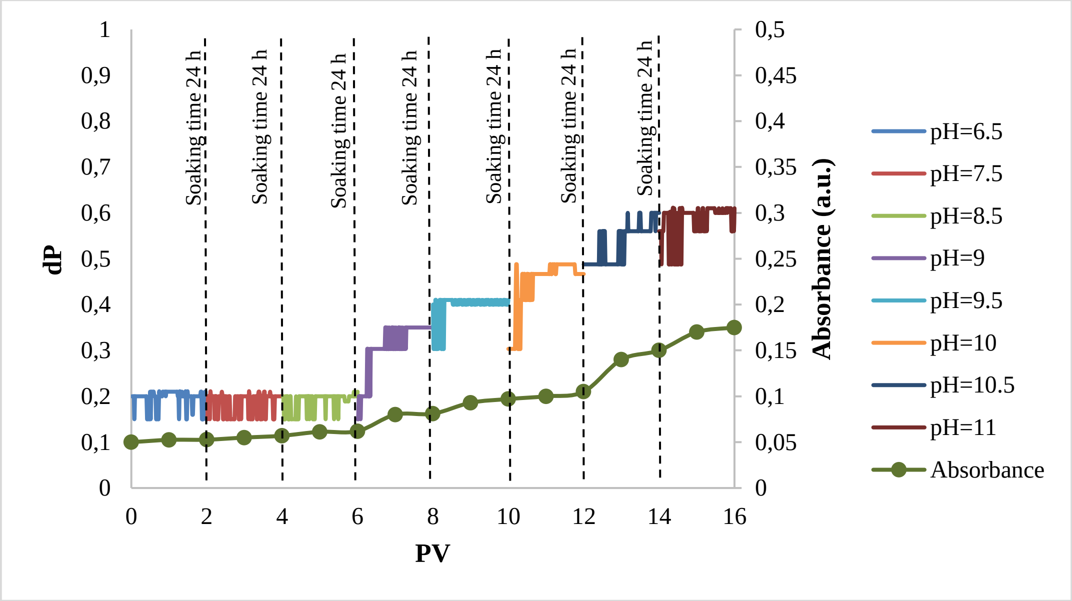

Figure 4.3 Pressure drops and light absorbance changes at different pH levels at 0.2 M NaCl salinity

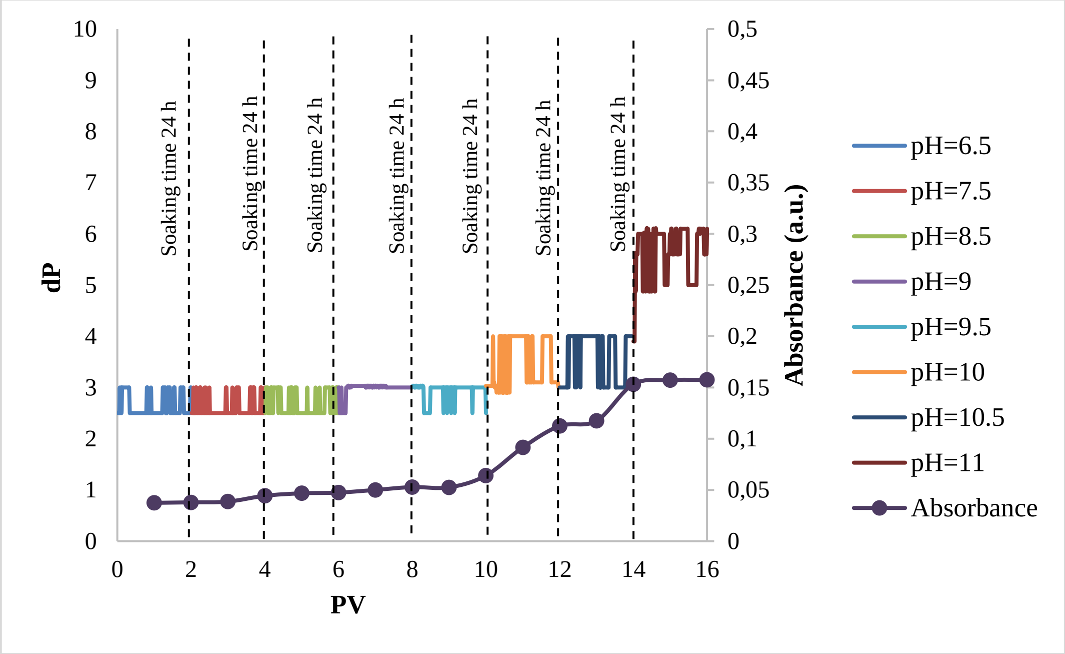

Figure 4.4 Pressure drops and light absorbance changes at different pH levels at 0.25 M NaCl salinity

After core flooding, effluent samples were analyzed using UV-VIS spectroscopy to detect the presence of fines. This detection was based on the increase in particle concentration in the effluent, which helped confirm the pressure drop results and monitor the critical pH. Spectroscopy results showed a breakthrough in light absorbance between pH 8 and 9 for 0.2 M NaCl, with the highest absorbance value of 0.18 recorded at pH 11 (Figure 4.3).

For brines with a salinity of 0.25 M NaCl, as illustrated in Figure 4.4, light absorbance increased sharply at pH 10, peaking at 0.15 at pH 11. Since these fines migrate with the produced fluid, they absorb light, leading to an increase in the light absorbance of the effluent.

These rapid changes in absorbance values may indicate mineral dissolution, which can affect rock permeability or porosity.

The results suggest that both pressure drop and light absorbance values increase with rising pH and salinity, confirming the presence of fines in the effluent. This integrated approach, combining coreflood tests and absorbance measurements, provides a more comprehensive understanding of the interaction between sand, fines, and brine. High light absorbance is a reliable indicator of the presence and migration of fines. However, UV-VIS spectroscopy is only one of several tools available for examining or measuring fines migration.

The average effluent absorbance for brine at the critical pH is presented in Table 4.6

Table 4.6 Average effluent absorbance for the critical pH

Brine salinity	Brine pH	Light absorbance
0.2 M NaCl	9	0.08 (a.u.)
0.25 M NaCl	10	0.1 (a.u.)

Overall, the core flooding tests provided experimental confirmation of critical pH values, with high-pressure drops measured at pH 9 for 0.2 M NaCl and pH 10 for 0.25 M NaCl (Table 4.7). It can be concluded that both methods of predicting critical pH are consistent.

Table 4.7 Experimental validation of critical pH predicted by DLVO theory.

Brine salinity	Modeled critical pH	Experimental critical pH
0.2 M NaCl	8	9
0.25 M NaCl	10	10

Predicting the critical pH for each salinity level is crucial for controlling fines migration and preventing formation damage. In this chapter, particle size, zeta potential, temperature, and ionic strength were considered as input parameters for predicting the critical pH. The uncertainties in key input parameters used in DLVO modeling, including zeta potential, Hamaker constant, ionic strength, and particle size, were systematically assessed in terms of error estimation for predicting the critical pH at which fines migration begins. The van der Waals attraction and electrical double layer repulsion energies, which combine to define the total particle-particle interaction energy, are a function of these parameters.

This study also gives an error estimation, which has a confidence value of $R^2 = 92\%$, which means that the predicted critical pH value predicted with the error estimation is accurate to an extent. With spherical particles and fixed ionic strength, this level of accuracy can be measured, with the precision of the measured inputs being sufficient to achieve this. The critical pH prediction was properly analyzed for error to ensure its reliability for better decision making regarding controlling fines migration in sandstone reservoirs.

Knowledge of the critical pH value as well as the different factors which affect the critical pH value in a brine, fine, and sand system may minimize the formation damage that may occur during alkaline water injection. Critical pH values for brines with salinities 0.2 M NaCl and 0.25 M NaCl were studied in this work below which fines detachment and further migration can be prevented.

Figure 4.5 shows that increasing the salt concentration of the injected brine has a one-to-one relationship with the critical pH of brine in rock. This is due to alkaline fluids and fluids with critical or higher salinity concentrations neutralizing the negative charge of the rock, thereby reducing electrostatic repulsion. EDL is a layer that surrounds particles in a system and creates an ionic cloud. Its thickness depends on various parameters, such as the surface charge, pH of the solution, and ionic strength. High salt brines have a higher ion concentration, which can compress the EDL due to the ability of ions to neutralize particle surface charges and reduce repulsion forces. Additionally, high salt concentrations may mitigate the effects of pH changes on the system, as ions from the brine can offset the increased hydroxide ions and surface charge. As a result, fine particles in the reservoir rock remain stable.

However, as shown in Figure 4.5, the critical pH values change stepwise during small changes in salinity when the salinity is below the critical concentration (0.2 M NaCl). It should be noted that the relationship between salinity and pH is complex and can be influenced by several factors.

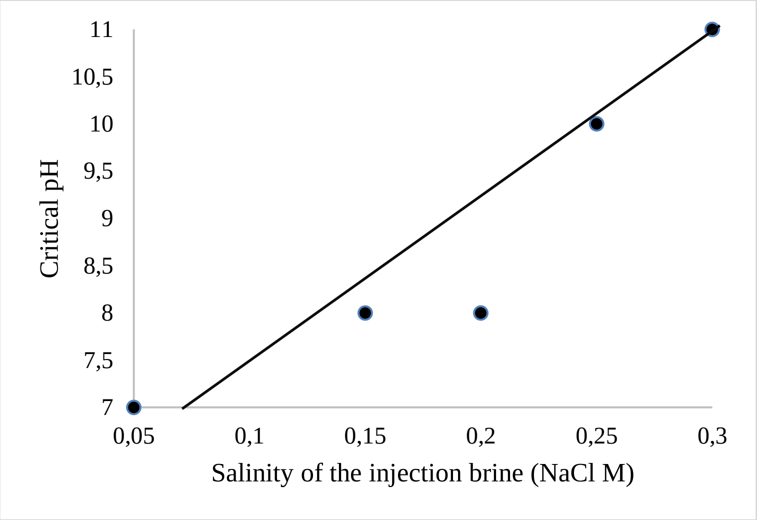

Figure 4.5 Dependency of critical pH on the salinity of injected brine.

One factor that may affect this relationship is zeta potential. Zeta potential helps to determine the stability of colloidal systems by measuring the surface charge of particles in a given solution. It is known that increasing ionic strength leads to an increase in zeta potential.

Therefore, in conditions of low salinity, the zeta potential will also be low. Consequently, a slight change in salinity will not cause a significant increase in zeta potential and, as a result, the change in critical pH may be negligible. Overall, although salinity can have an impact on the critical pH at which fine particles start to detach, there may not be a significant change in the critical pH value if the salinity is low.

To confirm the accuracy of the theory, two coreflood tests were performed, which showed results similar to those of the modeling. It makes the DLVO theory a useful tool to understand critical pH values under different conditions. To conclude, combining experimental, modeling, and reservoir data, the DLVO theory may help to reduce formation damage and optimize the alkaline flooding for oil recovery.

4.2 Modeling of Fines Migration during the High Injection Rate

4.2.1 Prediction of Critical Flow Rate by Improved DLVO Modeling to predict the Initiation of Fines Migration

As the flow rate increases, the significance of hydrodynamic forces becomes more pronounced. As shown in Figure 4.6, at a specific point, approximately 0.00001 m of fine particle radius, hydrodynamic (Fd) forces exceed electrostatic (Fe) and gravity (Fg) forces. At this point, fines begin to migrate. The critical velocity is 0.0002 m/sec. Additionally, the critical velocity decreases as the particle radius increases. This suggests that the effect of hydrodynamic forces on fine migration is influenced by particle size.

For example, at pH 8 and 0.00 M NaCl brine with 400 nm particle radius the critical velocity was 0.038 m/sec, much higher than 0.0002 m/sec. This indicates that the brine can flow through the rock more easily when pores are not obstructed by fine particles.

The critical velocity's dependence on particle or pore size can be attributed to the stress caused by fluids in the pores. When pore size decreases, a lower critical flow rate is required, resulting in additional stress due to pore constrictions. Furthermore, fluid viscosity can affect the flow rate, as higher viscosity increases hydrodynamic stress.

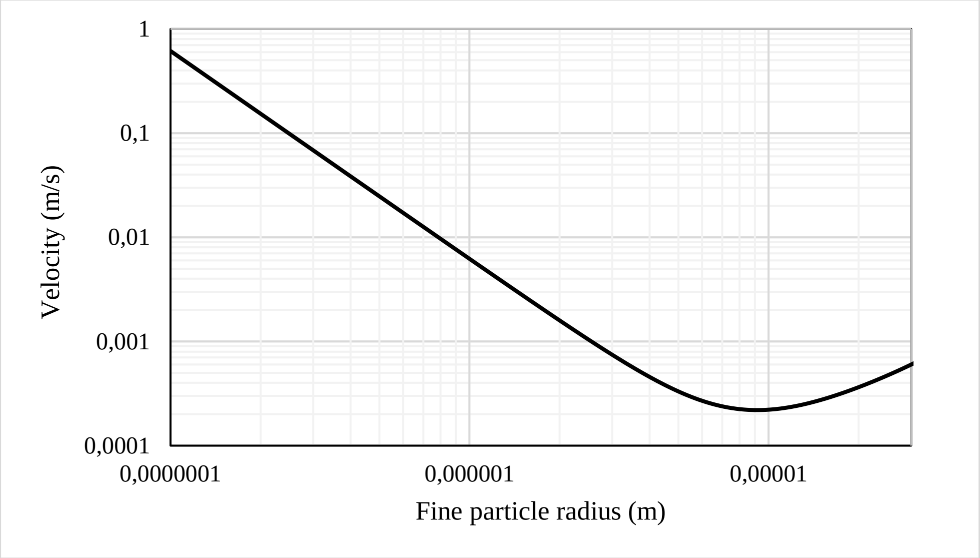

Figure 4.6 Critical velocities for 0.25 M NaCl brine with pH of 8 dependent on fine particle radius

4.2.2 Confirmation of the Model by the Experiment

The coreflood test was conducted on the upper Berea sandstone core sample to assess the effect of hydrodynamic forces and determine the critical velocity for the given brine. During the test, three PVs of 0.25 M NaCl brine with pH 8 were injected at a rate of 0.2 cc/min. Simultaneously, pressure drop (dP) was monitored through the core for each injected PV, as shown in Figure 4.7. Since the system's salinity decreased to 0.25 M, a 24-hour soaking period was provided to allow sufficient contact between fine particles, the rock surface, and the injection brine. This soaking time also ensured stability in the interaction forces.

After this soaking period, the same brine was injected at an increased flow rate of 1 cc/min to examine the potential for fines migration caused by hydrodynamic forces. However, no fines detachment was observed at flow rates of 0.2 and 1 cc/min. When the flow rate increased to 2 cc/min, a change in pressure drop was observed. Overall, the test showed a gradual change in flow rate and pressure drop, with 2 cc/min identified as the critical flow rate at which hydrodynamic forces were sufficient to initiate fines migration in the porous media system.

Absorbance measurements were taken for each PV to support the coreflood test results and confirm the presence of fines. At low flow rates (0.2 and 1 cc/min), the average absorbance of the effluent was low, nearly identical to that of the injection fluid. A change in absorbance was observed at the critical flow rate, with the absorbance values for each PV presented in Figure 4.7.

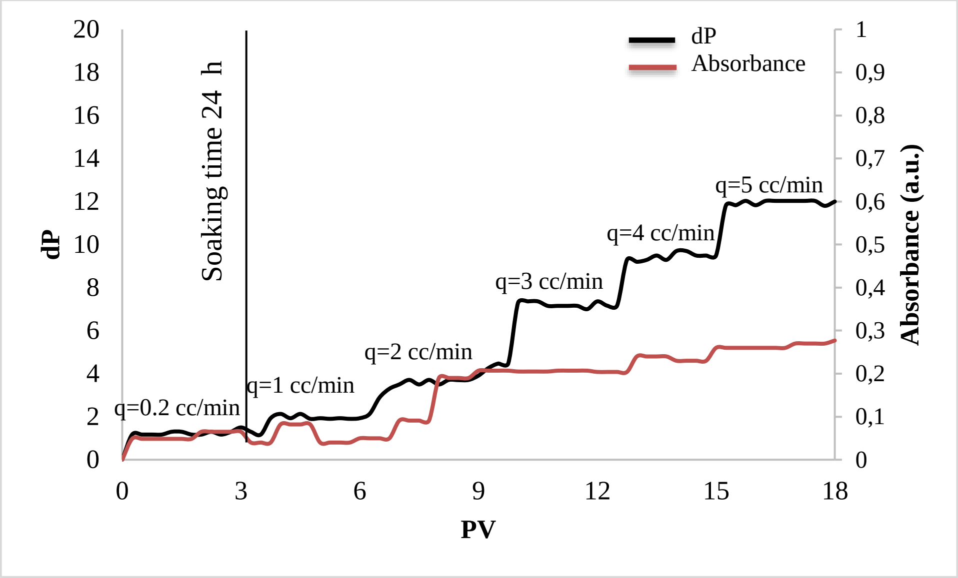

Figure 4.7 Pressure drop change at pH=8 for salinity 0.25 M NaCl

4.2.3 Critical pH at a High Rate

Although the critical flow rate is influenced by hydrodynamic forces, it is important to note that critical velocity is also affected by electrostatic interactions and gravity forces. Velocity is influenced by both attraction and repulsion forces, as well as the expansion of EDL. Consequently, it can be suggested that as pH increases or salinity decreases in the brine, the critical velocity may decrease. These electrostatic forces play a role in determining the critical pH at a given flow rate.

For the chosen pH value of 8 for 0.25 M NaCl brine, the critical flow rate was determined for both high and low rates. At low flow rates, the effect of attraction forces is more significant compared to repulsion forces. However, as the flow rate increases, a pH of 8 becomes critical for initiating fines migration. This is because hydrodynamic forces begin to dominate over both attraction and repulsion forces. As shown in Table 4.8, the velocity at which fines are released for the given pH was observed experimentally and by modeling, with results closely matching each other. Despite the dominance of hydrodynamic forces at higher flow rates, both interaction forces must be considered to estimate the velocity at which brine with a given pH is injected.

Table 4.8 Critical flow at pH 8, 0.25 M NaCl

Salinity (M)	pH	Modeled critical velocity (m/sec)	Experimental critical flow rate (m/sec)
0.25	8	2.2×10^{-4}	1.9×10^{-4}

Another factor to consider when estimating the parameters affecting fines release during brine injection at a specific flow rate is gravity force. Gravity force is influenced by the radius of the fine particles, as larger particles require more force to move. When considering brine injection parameters, the effect of gravity forces on fine particle initiation becomes more pronounced as flow rate or pH increases, while electrostatic attraction forces become less significant.

Error estimation in DLVO modeling for predicting the critical flow rate at which fines initially migrate involves examining uncertainties in input parameters such as zeta potential, particle size, and ionic strength, all of which affect DLVO interaction energies. The critical flow rate predicted at pH 8 and 0.25 M NaCl was evaluated against a calculated error of 13%. Variations in measured zeta potential under alkaline conditions and the sensitivity of double-layer repulsion energy to ionic strength contribute to this error. Standard error propagation techniques were used to estimate errors in the total interaction energy by accounting for the partial derivatives of the total interaction energy for each parameter. While a 13% error suggests moderate confidence in the model's ability to predict the critical flow rate, precise experimental measurements and a thorough understanding of surface charge forces in saline environments will be essential for improving accuracy.

5. CONCLUSIONS AND RECOMMENDATIONS

These studies aimed to predict critical pH and critical flow rate values using DLVO modeling in Upper Berea sandstone core samples. The DLVO model was applied to evaluate the interaction forces between sandstone rock surfaces and fine particles in a given colloidal system. In order to assess the applicability and validate the model, modeling and experimental work were done at room temperature for the single-phase fluid flow. It was shown in these data that DLVO is very close to the experimental test results. For instance, the method described in this study can be used to plan the waterflooding and alkaline flooding to recover more oil, or to gain knowledge of behavior in the reservoir, with minimal testing, once the critical parameters are measured in the field.

The first point to mention about the first is the calculation of the interaction forces with zeta potential, ionic strength, pH, salinity, and the fine particle size. From these parameters, the model for the colloidal system in the sand-rock surface, whose development was based on these parameters, was set. Experimental tests confirmed that the critical pH of the system is predicted by the model. Two types of brine salinities with critical salt concentrations and with a slightly higher value were employed for this prediction. Using these results, the critical pH of the onset of fines migration is predicted to depend on pH increase and salinity decrease using the DLVO model. Specifically, the model predicts that the pH at which fines migration begins for a salt concentration of 0.2 M NaCl is 8, whereas it rises to 10 for 0.25 M NaCl. We therefore conclude that well engineering based on DLVO modeling can be effectively bridged to experimental validation for optimally managing reservoirs and minimizing the formation damage.

The second step was to incorporate the DLVO model of electrostatic forces with hydrodynamic forces to establish a model for predicting critical flow rate. Errors of 13% were achieved in the model's ability to identify the flow rate threshold for fines migration initiation. The model correctly captures the fines detachment dynamics at this level of accuracy, while it demonstrates robustness to the fluid flow conditions. These results emphasize the validity of the DLVO theory as a basis for reservoir operations prediction and formation damage mitigation due to fines migration. The model was also validated by coreflood experiments with single-phase flow across a range of flow rates. Overall, the model can be used to predict fine particle release and movement during water injection into a sandstone reservoir with small clay particles on its surface.

Although acknowledging that DLVO modeling was successful in every way in terms of predictive accuracy and compatibility with experimental results, as pointed out above, the main limitation of the DLVO modeling approach has not been fully resolved in this work. It is consequently critical to move beyond these limitations to provide an outline of the research's future possibilities for the progression of the field.

Several points should be discussed in the plan.

1 There is a need to control the temperature during the work since both zeta potential and pH are highly dependent on temperature. It may help measure parameters and forces between rocks and fines more accurately. In this work, the measured temperature was room temperature; however, to understand formation conditions, there might be a possibility to consider a reservoir temperature.

2 To predict critical pH, there were used only NaCl brine, which is a monovalent brine. Since DLVO modeling also depends on parameters such as ionic strength, there is a need to check its applicability by considering divalent brines as well as monovalent types of brine.

3 Nowadays, most of the enhanced oil recovery methods are based on combining several methods into one. Therefore, there is a suggestion to integrate alkaline flooding with Nanotechnology and check the critical parameters in this condition. It can be effective since nanoparticles may positively affect the staying of fines on rock.

4 From the integration of the DLVO model's capability of predicting with the reservoir simulators, engineers and researchers can gain substantial information about the fluid–particle interactions in the system. With the integration of DLVO modeling with reservoir simulators, DLVO has additional uses besides oil recovery. This approach is crucial for modeling and controlling water movement in subsurface Sandstone aquifer systems. Sandstone formations are major aquifers, and quantitative estimates of water flow and transportation in these reservoirs are vital for successful water supply management.

6. REFERENCES

Agi, A., Junin, R., Jaafar, M. Z., Majid, Z. A., Amin, N. A. S., Sidek, M. A., ... & Oseh, J. (2023). Dynamic stabilization of formation fines enhances oil recovery of a medium permeability sandstone core at reservoir conditions. *Journal of Molecular Liquids*, *371*, 121107. https://doi.org/10.1016/j.molliq.2022.121107

Agmo Hernández, V. An overview of surface forces and the DLVO theory. *ChemTexts* **9**, 10 (2023). https://doi.org/10.1007/s40828-023-00182-9

Ali, M., Al-Yaseri, A., Awan, F. U. R., Arif, M., Keshavarz, A., & Iglauer, S. (2022). Effect of water-soluble organic acids on wettability of sandstone formations using streaming zeta potential and NMR techniques: Implications for CO2 geo-sequestration. *Fuel*, *329*, 125449. https://doi.org/10.1016/j.fuel.2022.125449

Al-Sarihi, A., Zeinijahromi, A., Genolet, L., Behr, A., Kowollik, P., & Bedrikovetsky, P. (2018, October). Fines migration as an EOR method during low salinity waterflooding. In *SPE Asia Pacific Oil and Gas Conference and Exhibition* (p. D021S008R004). SPE. https://doi.org/10.2118/192070-MS

Arab, D., & Pourafshary, P. (2013). Nanoparticles-assisted surface charge modification of the porous medium to treat colloidal particle migration induced by low salinity water flooding. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, *436*, 803-814. https://doi.org/10.1016/j.colsurfa.2013.08.022

Askar, N., Muneer, R., & Pourafshary, P. (2023). Effect of wettability and phase distribution on critical salt concentration for fines migration initiation in sandstone reservoirs. *Journal of Molecular Liquids*, *390*, 123113.https://doi.org/10.1016/j.molliq.2023.123113

Assef, Y.; Arab, D.; Pourafshary, P. Application of nanofluid to control fines migration to improve the performance of low salinity water flooding and alkaline flooding. *J. Pet. Sci. Eng.* **2014**, *124*, 331– 340, DOI: 10.1016/j.petrol.2014.09.023

Austad, T., RezaeiDoust, A., & Puntervold, T. (2010, April). Chemical mechanism of low salinity water flooding in sandstone reservoirs. In *SPE Improved Oil Recovery Conference?* (pp. SPE-129767). Spe. https://doi.org/10.2118/129767-MS

Bagrezaie, M. A., Dabir, B., & Rashidi, F. (2022). A novel approach for pore-scale study of fines migration mechanism in porous media. *Journal of Petroleum Science and Engineering*, *216*, 110761. https://doi.org/10.1016/j.petrol.2022.110761

Bai, M., Liu, Z., Zhan, L., Yuan, M., & Huang, Y. (2023b). Effect of pore size distribution and colloidal fines of porous media on the transport behavior of micro-nano-bubbles. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, *660*, 130851. https://doi.org/10.1016/j.colsurfa.2022.130851

Barnaji, M. J., Pourafshary, P., & Rasaie, M. R. (2016). Visual investigation of clay minerals' effects on oil recovery enhancement by low salinity water flooding. *Fuel*, *184*, 826-835. https://doi.org/10.1016/j.fuel.2016.07.076

Bohinc, K., Kralj-Iglič, V., & Iglič, A. (2001). Thickness of electrical double layer. Effect of ion size. *Electrochimica Acta*, *46*(19), 3033–3040. https://doi.org/10.1016/s0013-4686(01)00525-4

Bradford, S. A., Torkzaban, S., & Shapiro, A. (2013). A theoretical analysis of colloid attachment and straining in chemically heterogeneous porous media. *Langmuir*, *29*(23), 6944-6952. https://doi.org/10.1021/la4011357

Chatterjee, J., & Wasan, D. T. (1998). A kinetic model for dynamic interfacial tension variation in an acidic oil/alkali/surfactant system. *Chemical engineering science*, *53*(15), 2711–2725. https://doi.org/10.1016/S0009-2509(98)00093-1

Chavan, M.; Dandekar, A.; Patil, S.; Khataniar, S. Low-Salinity-Based Enhanced Oil Recovery Literature Review and Associated Screening Criteria. *Pet. Sci.* **2019**, *16* (6), 1344–1360. doi:10.1007/s12182-019-0325-7

Chequer, L., C. Nguyen, G. Loi, A. Zeinijahromi, and P. Bedrikovetsky. "Fines migration in aquifers: Production history treatment and well behaviour prediction." *Journal of Hydrology* 602 (2021): 126660. https://doi.org/10.1016/j.jhydrol.2021.126660

Compère, F., Porel, G., & Delay, F. (2001). Transport and retention of clay particles in saturated porous media. Influence of ionic strength and pore velocity. *Journal of Contaminant Hydrology*, *49*(1–2), 1–21. https://doi.org/10.1016/s0169-7722(00)00184-4

Elimelech, M., Gregory, J., Jia, X., 2013. Particle Deposition and Aggregation: Measurement, Modelling and Simulation. Butterworth-Heinemann, Oxford, UK.

Gao, B., Saiers, J. E., & Ryan, J. N. (2004). Deposition and mobilization of clay colloids in unsaturated porous media. *Water Resources Research*, *40*(8). https://doi.org/10.1029/2004wr003189

Giraldo, L. J., Diez, R., Acevedo, S., Cortés, F. B., & Franco, C. A. (2021). The effects of chemical composition of fines and nanoparticles on inhibition of formation damage caused by fines migration: Insights through a simplex-centroid mixture design of experiments. *Journal of Petroleum Science and Engineering*, *203*, 108494.https://doi.org/10.1016/j.petrol.2021.108494

Gong, H., Li, Y., Dong, M., Ma, S., & Liu, W. (2016). Effect of wettability alteration on enhanced heavy oil recovery by alkaline flooding. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, *488*, 28-35. https://doi.org/10.1016/j.colsurfa.2015.09.042

Gregory, J. Approximate expressions for retarded van der Waals interaction. *J. Colloid Interface Sci.* **1981**, *83*, 138– 145, DOI: 10.1016/0021-9797(81)90018-7

Gustafsson, J., Mikkola, P., Jokinen, M., & Rosenholm, J. B. (2000). The influence of pH and NaCl on the zeta potential and rheology of anatase dispersions. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, *175*(3), 349-359. https://doi.org/10.1016/S0927-7757(00)00634-8

Israelachvili, J. N. Van der Waals forces between particles and surfaces. Intermolecular and surface forces 2011, 3, 253–289. DOI: 10.1016/b978-0-12-375182-9.10013-2

Ji, S., Li, X., Meng, X., Su, X., & Qing, L. (2023). Coupled effect of pH and kaolinite colloids on antibiotic transport in porous media. *Pedosphere*. https://doi.org/10.1016/j.pedsph.2023.01.003

Johnson, W. P., Pazmiño, E., & Ma, H. (2010). Direct observations of colloid retention in granular media in the presence of energy barriers and implications for inferred mechanisms from indirect observations. *Water Research*, *44*(4), 1158–1169. https://doi.org/10.1016/j.watres.2009.12.014

Karazincir, O., Williams, W., & Rijken, P. (2017, October). Prediction of fines migration through core testing. In *SPE Annual Technical Conference and Exhibition?* (p. D031S039R003). SPE. https://doi.org/10.2118/187157-MS

Khilar, K. C., & Fogler, H. S. (1984). The existence of a critical salt concentration for particle release. *Journal of Colloid and Interface Science*, *101*(1), 214–224. https://doi.org/10.1016/0021-9797(84)90021-3 Musharova et al. (2012)

Khilar, K. C., & Fogler, H. S. (1987). *Colloidally Induced Fines Migration in Porous Media. Reviews in Chemical Engineering, 4(1-2).* doi:10.1515/revce.1987.4.1-2.41

Kia, S. F., Fogler, H. S., & Reed, M. G. (1987). Effect of pH on colloidally induced fines migration. *Journal of colloid and interface science*, *118*(1), 158-168. https://doi.org/10.1016/0021-9797(87)90444-9

Labille, J., Harns, C., Bottero, J. Y., & Brant, J. (2015). Heteroaggregation of titanium dioxide nanoparticles with natural clay colloids. *Environmental science & technology*, *49*(11), 6608-6616. https://doi.org/10.1021/acs.est.5b00357

Liu, J., Hwang, Y. S., & Lenhart, J. J. (2015). Heteroaggregation of bare silver nanoparticles with clay minerals. *Environmental Science: Nano*, *2*(5), 528-540. 10.1039/C5EN00130G

Ma, Q., Li, H., & Li, Y. (2020). The study aims to improve oil recovery through the change in clay state during low salinity water flooding in sandstones. *ACS omega*, *5*(46), 29816-29829.https://doi.org/10.1021/acsomega.0c03849

Madadizadeh, A., Sadeghein, A., & Riahi, S. (2022). Effects of nano-silica on fine migration and location distribution of blockage at different pH and temperatures: Modelling and experimental studies. *The Canadian Journal of Chemical Engineering*, *100*(10), 2881-2893. https://doi.org/10.1002/cjce.24353

Mansour, M., Moustafa, E. A., Eleraki, M., & Noah, A. (2020). A novel approach of fines migration control using nanoparticle through zeta potential measurements. *Petroleum & Coal*, *62*(3). https://www.researchgate.net/publication/343227182

Mehdizad, A., Sedaee, B., Pourafshary, P., “Visual investigation of the effect of clay-induced fluid flow diversion on oil recovery, as a low-salinity water flooding mechanism”, Journal of Petroleum Science and Engineering, 2022, 209, 109959https://doi.org/10.1016/j.petrol.2021.109959

Muneer, R., Hashmet, M. R., & Pourafshary, P. (2020). Fine migration control in sandstones: Surface force analysis and Application of DLVO Theory. *ACS Omega*, *5*(49), 31624–31639. https://doi.org/10.1021/acsomega.0c03943

Muneer, R., Hashmet, M. R., & Pourafshary, P. (2022). DLVO modeling predicts critical salt concentration to initiate fine migration pre- and post-nanofluid treatment in sandstones. *Spe Journal*, *27*(04), 1915–1929. https://doi.org/10.2118/209588-pa

Muneer, R., Pourafshary, P., & Hashmet, M. R. (2023). An integrated modeling approach to predict critical flow rate for fines migration initiation in sandstone reservoirs and water-bearing formations. *Journal of Molecular Liquids*, p. *376*, 121462. https://doi.org/10.1016/j.molliq.2023.121462

Muneer, R., Pourafshary, P., & Hashmet, M. R. (2023). An integrated modeling approach to predict critical flow rate for fines migration initiation in sandstone reservoirs and water-bearing formations. *Journal of Molecular Liquids*, *376*, 121462.

Mungan, N. (1965). Permeability reduction through changes in pH and salinity. *Journal of Petroleum Technology*, *17*(12), 1449–1453. https://doi.org/10.2118/1283-pa

Musharova, D.; Mohamed, I. M.; Nasr-El-Din, H. A. Detrimental effect of temperature on fines migration in sandstone formations. SPE International Symposium and Exhibition on Formation Damage Control, 2012. 10.2118/150953-MS https://doi.org/10.2118/150953-MS

Nasralla, R. A., Bataweel, M. A., & Nasr-El-Din, H. A. (2013). Investigation of wettability alteration and oil-recovery improvement by low-salinity water in sandstone rock. *Journal of Canadian Petroleum Technology*, *52*(02), 144-154. https://doi.org/10.2118/146322-PA

Nasralla, R.A., Alotaibi, M.B., Nasr-El-Din, H.A., 2011. Efficiency of oil recovery by low salinity water flooding in sandstone reservoirs. In: SPE 144602, SPE Western North American Region Meeting, Anchorage, Alaska, U.S.A.

Ochi, J., & Vernoux, J. F. (1998). Permeability decreases in sandstone reservoirs by fluid injection: hydrodynamic and chemical effects. *Journal of Hydrology*, *208*(3-4), 237-248. https://doi.org/10.1016/S0022-1694(98)00169-3

Ohshima, H., & Takeda, S. I. (2024). A New Method for Calculating the Hamaker Constant Based on the Hansen Solubility Parameters for Nonpolar Liquids. *Colloids and Interfaces*, *8*(2), 14. https://doi.org/10.3390/colloids8020014

Rosenbrand, E., Haugwitz, C., Jacobsen, P. S. M., Kjøller, C., & Fabricius, I. L. (2014). The effect of hot water injection on sandstone permeability. *Geothermics*, *50*, 155-166. https://doi.org/10.1016/j.geothermics.2013.09.006

Rosenbrand, E., Kjøller, C., Riis, J. F., Kets, F., & Fabricius, I. L. (2015). Different effects of temperature and salinity on permeability reduction by fines migration in Berea sandstone. *Geothermics*, *53*, 225-235. https://doi.org/10.1016/j.geothermics.2014.06.004

Russell, T., Chequer, L., Borazjani, S., You, Z., Zeinijahromi, A., & Bedrikovetsky, P. (2018). *Formation Damage by Fines Migration. Formation Damage During Improved Oil Recovery, 69–175.* doi:10.1016/b978-0-12-813782-6.00003-8

Sarkar, A. K., & Sharma, M. M. (1990). Fines migration in Two-Phase flow. *Journal of Petroleum Technology*, *42*(05), 646–652. https://doi.org/10.2118/17437-pa

Schramm, L. L., Mannhardt, K., & Novosad, J. J. (1991). Electrokinetic properties of reservoir rock particles. *Colloids and surfaces*, *55*, 309-331. https://doi.org/10.1016/0166-6622(91)80102-T

Sheng, J. J. (2013, April). A comprehensive review of alkaline-surfactant-polymer (ASP) flooding. There was a joint technical conference in the *SPE Western Regional & AAPG Pacific section meeting in 2013*. OnePetro. https://doi.org/10.1002/apj.1824

Sourani, Saeed, et al. (2014). "Effect of fluid flow characteristics on migration of nanoparticles in porous media." *Geomaterials* 2014. 10.4236/gm.2014.43008

Tang, G. Q., & Morrow, N. R. (1999). Influence of brine composition and fines migration on crude oil/brine/rock interactions and oil recovery. *Journal of petroleum science and engineering*, *24*(2-4), 99-111. https://doi.org/10.1016/S0920-4105(99)00034-0

Trefalt, G., & Borkovec, M. (2014). Overview of DLVO theory. *Laboratory of Colloid and Surface Chemistry, University of Geneva, Switzerland*, *304*. https://docplayer.net/20731880-Overview-of-dlvo-theory.html#google_vignette

Vaidya, R. N., & Fogler, H. S. (1992). Fines migration and formation damage: influence of pH and ion exchange. *SPE production engineering*, *7*(04), 325-330. https://doi.org/10.2118/19413-PA

Valdya, R., & Fogler, H. S. (1992). Fines migration and formation damage: influence of pH and ion exchange. SPE Production Engineering, 7(04), 325–330. https://doi.org/10.2118/19413-pa

Wang, Y., Yu, M., Bo, Z., Bedrikovetsky, P., & Le-Hussain, F. (2021). Effect of temperature on mineral reactions and fines migration during low-salinity water injection into

Berea sandstone. *Journal of Petroleum Science and Engineering*, *202*, 108482. https://doi.org/10.1016/j.petrol.2021.108482

Yan, Z., Huang, X., & Yang, C. (2015). Deposition of colloidal particles in a microchannel at elevated temperatures. *Microfluidics and nanofluidics*, *18*, 403-414. 10.1007/s10404-014-1448-1

Yang, Y., Yuan, W., Hou, J., & You, Z. (2022). Review on physical and chemical factors affecting fines migration in porous media. *Water Research*, *214*, 118172. https://doi.org/10.1016/j.watres.2022.118172

Yang, Y., Yuan, W., Hou, J., & You, Z. (2022). Review on physical and chemical factors affecting fines migration in porous media. *Water Research*, *214*, 118172. https://doi.org/10.1016/j.watres.2022.118172

You, Z., Badalyan, A., Yang, Y., Bedrikovetsky, P., & Hand, M. (2019). Fines migration in geothermal reservoirs: Laboratory and mathematical modeling. *Geothermics*, *77*, 344-367. https://doi.org/10.1016/j.geothermics.2018.10.006

7. APPENDICES

Nomenclature
A = core cross-sectional area, cm^2
A_H = Hamaker constant, = 1.52×10^{-20} J
B = formation volume factor, RB/STB
e = electron charge, = 1.60×10^{-19} C
d = core diameter, cm
F_d = drag force, kg-m/s^2
F_e = effective electrostatic force, kg-m/s^2
F_g = gravitational force, kg-m/s^2
F (k_a) = Henry's function
F_l = lift force, kg-m/s^2
h = formation thickness, ft
h = separation distance, nm
h_o = minimum equilibrium distance, m
H = dimensionless distance = h/r_f
I_l = lift lever arm, m
I_d = drag lever arm, m
I_s = ionic strength of permeating fluid, M
k = formation permeability, mD
k = inverse Debye length, m^{-1}
k_B = Boltzmann constant, = 1.38×10-23 JK^{-1}
k_s = damage permeability, mD
L = core length, cm
M = molarity, mol/liter
M_d = viscous surface stress, kg-m^2 /s^2
N_A = Avogadro's number = 6.02214×1023 $mole^{-1}$
pH = pH of injection fluid
P_e = external boundary pressure, psi
P_{wf} = wellbore flowing pressure, psi
q = flow rate, cc/sec
r_e = drainage radius, ft
r_f = fine particle radius, m
r_p = pore radius = 0.00005 m
r_w = wellbore radius, ft
S = skin factor
T = absolute temperature, = 297.15 K
U_E = electrophoretic mobility, V
v = injection velocity, m/s
V_{AB} = acid-base interaction energy, J
V^o_{AB}= hydrophobic/hydrophilic interaction, J
V_{BR} = Born repulsion energy, J
V_{EDL} = Electrical double-layer energy, J
V_{LVW} = London-van der Waals energy, J
V_T = total interaction energy, J
z = valence of the ion
ζ = zeta potential, mV
μ = fluid viscosity, kg/m-s

σ = atomic collision diameter, = 5×10^{-10} m
ε_m = dielectric constant of water = 80
ε_o = permittivity of the vacuum, = 8.85×10^{-12} F.m-1
η = viscosity of the solution, kg.$m^{-1}s^{-1}$
λ = decay length of liquid molecules, m
π = pi = 3.1416
Δp = pressure drop, psi