Near-Wellbore Permeability Damage by Fines Migration in

Steam Assisted Gravity Drainage Wells

by

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Abstract

This thesis investigates the flow performance impairment or permeability damage under the fines migration process near the SAGD wellbore producers completed with sand control screens. A new sand retention testing (SRT) procedure was developed to replicate a more representative fines migration process in SAGD wellbore conditions to evaluate the flow performance of sand control screens. The investigation factors included different sand control screen specifications, flow rate, flow salinity, fines content, and sand and fine particles size distributions. The research was conducted in two experimental and numerical stages.

The first stage comprised extensive SRT experiments to investigate the hydrodynamic and chemical effects of the fines migration process, evaluate the reliability of previous testing procedures for replicating representative fines migration process in SRT experiments, and troubleshoot the set-up deficiencies.

The experimental results indicated a non-monotonic behavior of permeability with an initial decrease followed by an increasing trend for the near screen interval of the sand pack, inconstant with core flooding and field observations. This behavior was attributed to the dominant effect of releasing fine particles from or near the pore throats compared with retaining fine particles over the thin pore throats by the hydrodynamic effects only. A monotonic decreasing behavior of the permeability was observed under the chemical effect of the fines migration when high saline saturating fluid was displaced with a low saline brine, representing near SAGD wellbore conditions. The sand screens with a low open flow area and narrow aperture caused high permeability loss under the same flow conditions. Higher salinity reduction yielded higher mobilized fines concentration, causing high permeability loss of the sample.

A laboratory-based numerical modeling approach was conducted in this research to simulate the fines migration process in the SRT setup, considering the sand screen geometry. With sufficient accuracy, the model could match the observed dimensionless pressure drops at different sample intervals. The model incorporated four calibration parameters concerning filtration of fine particles at pore throats, fine particles velocity, and the empirical permeability loss correlation parameters. The model calibration results confirmed that the matching parameters were nearly independent of the sand screen. However, they were different for different flow salinities, confirming their dependency on flow properties along with the porous media.

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Chapter 1: Introduction

1.1 Overview and Problem Statement

Bitumen in deeper oil sands is recovered through thermal recovery processes such as steam-assisted gravity drainage (SAGD). Sand control devices (SCD) are essential components of wellbore completions for the horizontal SAGD wells in unconsolidated oil sands. A proper SCD design should minimize sand production while creating the least resistance to flow. This flow resistance could be caused by the device's relatively low open flow area (OFA) and accumulation of migrating fine particles into the porous media near the screen in sand formations with considerable fines content. The latter, resulting from the fines migration process, can significantly impair the near-wellbore permeability, reducing the well productivity.

The fines migration is a complex process involving many interacting factors related to the porous medium, carrier fluid, environment (temperature), well operation, and well completion (SCD). This process includes the release (detachment), transport, and capture (retention) of fine particles within porous media due to hydrodynamic and physicochemical forces [1-2]. Under the flow velocities and salinities above and below a critical value, respectively, high pH and high-temperature conditions, the net repulsive forces are dominant, yielding the release of fine particles from grain surfaces [3]. It is usually a near-wellbore phenomenon where flow velocities are high [3].

Fine particles are recognized as clay and non-clay materials smaller than 37 μm or 44 μm [4-6]. Kaolinite and illite are the primary migratory clay minerals in oil sands that could plug the pore throats [7]. The plugging or retention mechanisms could be size exclusion (single-particle straining), gravity and inertial retardation, and direct interception (mechanical and hydrodynamic bridging by multiple particles) [8-10].

Although significant past studies [2,4,11-14] have been conducted on the effect of many factors, such as flow velocity, salinity, salt composition, pH, temperature, particle size distribution (PSD), effective stress, fines content, wettability, and multi-phase flow condition on the fines migration process, the contribution of the SCD has not been adequately explored. Theoretically, SCD design would impact the production and accumulation of fine particles behind the screen.

Standalone screens such as slotted liner (SL), wire-wrapped screen (WWS), and punched screen (PS) have been widely employed in horizontal SAGD wells [15-16]. The slotted liner (SL) is popular among the other standalone screens due to its low manufacturing costs and adequate mechanical integrity when running in long horizontal SAGD wells [17-20]. Other options benefit sand formations with severe plugging issues [19, 21]. It is expected that a larger aperture and higher flow areas reduce the screen and near-screen plugging by fine particles. Plugging of slotted liner screens is a common problem in SAGD wells [17]. As schematically shown in **Figure 1.1,** slotted liners offer a relatively low open flow area, causing flow convergence and increasing flow velocity by a factor of 10-20 through the device [22]. The flow convergence causes the inertial retardation of fine particles near the screen, which results in the retention and accumulation of fine particles [23].

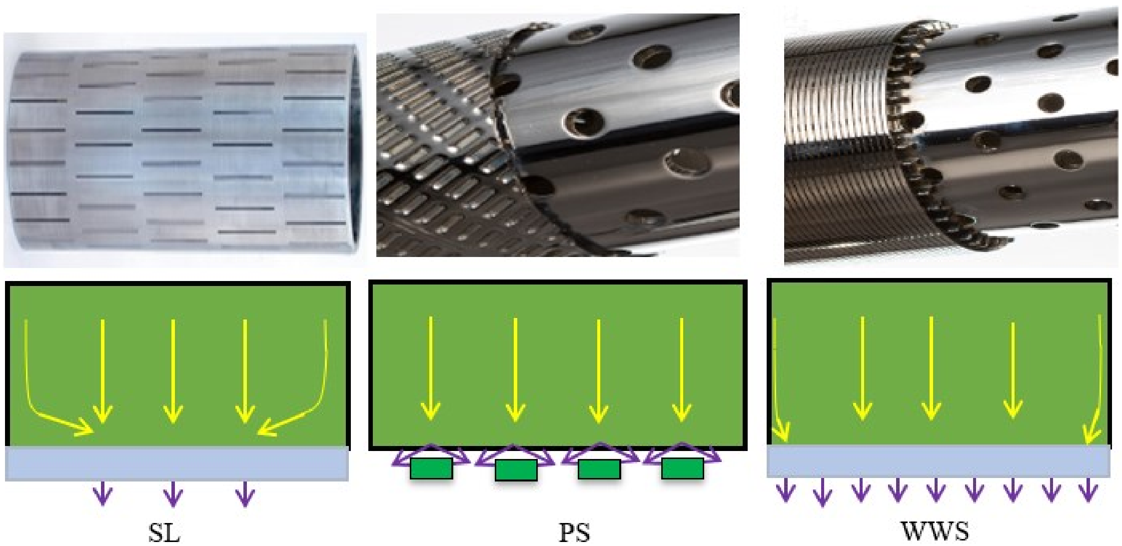

Figure 1. 1: Different sand control screens with flowlines pattern schematics [24, 25].

The plugging of slotted liners in SAGD wells is a common problem [17]. In addition to the wellbore damage caused by corrosion and scaling, the effect of migrating fine particles has been reported for the SAGD wells [17, 26]. A high retention concentration of fine particles can cover the SCD openings and plug pore spaces in the near-wellbore region.

Recent sand retention testing (SRT) experimental works, replicating near-wellbore SAGD wells conditions, provided limited observations on fine particles mobilization and retention near an SCD coupon [15-16,27-31]. In these tests, the test duration is short (maximum three pore volume injections), while the fines migration process is long-term with permeability stabilization after high pore volume injections. Also, the effect of salinity change as a possible scenario around the SAGD wells with steam condensate has not been investigated. Therefore, the tests would be primarily suitable for relatively clean sands (low fines content), where the test only captures the flow performance of the SCD by the sand retention layer over the screen.

Regarding modeling and simulating the fines migration process in porous media, both micro-scale models (population balance models, random walks models, and direct pore-scale simulation) and macro-scale models have been applied [2,32-34]. Macro-scale models are based on mass balance and momentum equations for the fluid (Darcy's flow) and fine particles transport (convection-diffusion equation) along with macroscopic rate equations for the release and retention of fine particles [2,11,35-36]. These models have been mainly applied to the consolidated sand formations, and the well completion (SCD) effect has not been considered.

This research attempts to advance the current sand retention testing procedures for SCD evaluation, to adequately replicate and look into the fines migration process under representative SAGD well conditions. In addition, a macroscopic numerical model is developed incorporating the SCD geometry to assess the fines migration process and flow performance in an SRT setup.

1.2 Research Objectives

The general objective is to investigate the permeability impairment by fines migration around the sand control screens around the SAGD producers, implementing an integrated experimental and numerical approach. More specifically, the objectives are as follows.

- Develop a reliable sand retention testing (SRT) procedure accounting for the fines migration around the SAGD production wells
- Evaluate the sand control screen-porous medium interaction in an SRT setup under the fines migration process
- Develop a 3D macroscopic numerical model, incorporating the fines migration process in an SRT setup

1.3 Research Hypothesis

This research is carried out based on hypotheses as follows:

- The fines migration process influences the SCD flow performance in formations with high fines content at high pore volume injections.
- The current design criteria of the SCD based on short-term flow performance are only suitable for clean or fines-free formations.
- A representative SRT testing procedure can be developed to compare the flow performance of SCDs for SAGD wells.

- A numerical model based on macroscopic release and retention mechanisms of fine particles within porous media can be established and calibrated to simulate the fines migration process in an SRT experiment.

1.4 Research Methodology

The research was carried out in two primary experimental and mathematical steps. The experimental work involves more than 50 sand retention testing (SRT) experiments, including repeatability and diagnosing tests. The tests were conducted based on previous and new modified testing procedures to investigate the flow performance of different designs of SCD under the fines migration process. Initially, a large-scale SRT setup was used, accomodating a 12-inch length sand sample and a 6-inch diameter screen coupon. Later, a smaller SRT cell (2.5-inch diameter) was utilized to perform more efficient fines migration testing with more accurate measurements.

The mathematical work involves solving the coupled governing equations for the fines migration process on a 3D numerical grid using the finite element method implemented in COMSOL Multiphysics. The grid incorporates the sand sample and SCD geometry. Initial and boundary conditions consistent with experiments were appropriately set to solve unknown variables, including pressure, mobile fines concentration, and retained fines concentration. A steady-state grid-dependency study was also performed to find an optimum and appropriate grid for the simulation. The non-linear least-squares optimization algorithm, Levenberg-Marquardt, was used to determine four model parameters by matching the dimensionless pressure drops for the experiments and the model at different intervals along the sample length.

1.5 Thesis Outline

This thesis is paper-based formatted, containing five chapters. Chapter 1 presents a brief background and an overview of the research problem and gaps, the objectives, hypotheses, and research methodology.

Chapter 2 is a comprehensive literature review on the fines migration process focusing on SAGD well conditions. This chapter discusses the experimental and field observations of fines migration in unconsolidated oil sands, influencing factors, and previous SRT experiments. At the end of this chapter, a general workflow is presented for SCD design in unconsolidated sands to plugging with fines migration.

Chapter 3 presents the experimental investigations of the fines migration process in a large-scale SRT facility using different sand screen coupons and sand PSDs. These experiments investigate the fines migration process under both hydrodynamic and chemical effects representative of flow conditions in SAGD wells. At the end of this chapter, a reliable testing procedure is proposed for the fines migration evaluation in SRT experiments consistent with SAGD well conditions through analysis and discussion of the results.

Chapter 4 represents the experimental and numerical modeling results of flow performance of different sand screen coupons under the fines migration process based on the new testing procedure and using a small-scale SRT setup. This chapter presents full details of the numerical modeling of the fines migration process in SRT setup, model calibration, validation, and sensitivity analysis.

Chapter 5 contains the conclusions, research contributions, and future work.

Nomenclature

SAGD: Steam Assisted Gravity Drainage

SCD: Scaled Control Device

SL: Slotted Liner

WWS: Wire-Wrapped Screen

PS: Punched Screen

SRT: Sand Retention Testing

OFA: Open to Flow Area

PSD: Particle Size Distribution

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Chapter 2: A Review of Fines Migration around Steam Assisted Gravity Drainage Wellbores

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2.1 Preface

This paper reviews the state-of-the-art experimental and theoretical methods on fines migration around Steam Assisted Gravity Drainage (SAGD) wellbores. The in-situ migratory particles can deposit in the pore space, resulting in pore throat plugging within the porous medium. This process damages the permeability around the sand control screen. This review includes field observations, experimental works, and simulations solving fines migration mathematically.

Field observations indicate higher pressure differentials between the SAGD injector and producer due to the plugging of the sand control screen and surrounding formation. Coreflooding experiments confirm that the fines migration process is an essential contributing factor to the permeability damage near the SAGD wellbores. Macroscopic analytical models have also been extensively used at the lab scale to predict the permeability variation by the fines migration. The modeling studies are focused mainly on consolidated sandstones, but the impact of sand control devices has not been incorporated.

Many papers have been published to describe the influential factors controlling the fines migration process. However, the interaction between the wellbore completion and surrounding sand from the fines migration perspective has not been adequately explored. Despite numerous limitations in representing the reality near the SAGD wellbores, sand control testing procedures provide a short-term evaluation of the sand retention and flow performances of the sand control device in unconsolidated sand. However, these tests do not account for the transient behavior and long-term permeability variation caused by the fines migration process. This paper presents an integrated general-purpose procedure for designing sand control devices in SAGD wells, addressing the gaps in this review.

2.2 Introduction

Steam-assisted gravity drainage (SAGD) is the most common thermal recovery method for in-situ bitumen extraction in unconsolidated Alberta oil sands. The SAGD process involves the steam injection into a horizontal injector well drilled about five meters above the horizontal producer well close to the oil sands bed. The high-temperature steam heats the bitumen at the edges of a steam chamber developed around the injector well. The melted bitumen, along with condensate water, flows by gravity toward a liquid pool above the producer well and is pumped to the surface [1].

SAGD wells are equipped with sand control screens to prevent excessive sand production while creating the least resistance against the flow of reservoir fluids and fines. Fines migration is generally noticeable in unconsolidated sands [2]. Fine particles are known as very small loose particles in the reservoir that can pass through mesh screens of size 400 (37 μm) [3] or size 325 (44 μm) [4, 5]. These particles may contain clay minerals (kaolinite, illite, smectite, chlorite) and non-clay minerals (quartz, silica, feldspar, calcite, dolomite) [3, 6].

Fine particles are initially attached to the coarser grains by the net attractive surface forces and gravitational force and are prone to migration [7]. When the wetting phase starts to flow in the reservoir, fine particles may be entrained in the flow by net repulsive surface and hydrodynamic forces [7, 8, 9]. The mobilized particles migrate with the flow inside the porous medium and may plug the thin pore throats or accumulate behind previously bridged particles [10]. The retention of fine particles can significantly damage the permeability of the porous medium [11]. The release and retention of fine particles in the porous medium around the wellbore (in this text referred to as the "completion zone") is a complex process involving several interacting phenomena, such as organic and inorganic scaling.

Theoretically, the sand control screen can influence the fines migration, including the release and retention of the fines and fine particles production into the wellbore [12]. Indeed, they are inherently related to the screen aperture size and open flow area (OFA), causing flow convergence and spatially increasing flow velocities by a factor of 10-20 through the device [13]. The flow convergence increases the inertial retardation effect, which increases local fines concentration in the completion zone [12]. Fines retention, mobilization, and production would increase or decrease the completion zone's permeability over time [13, 14].

This paper integrates previous findings on fines migration in thermal wells from various experimental and theoretical studies. It discusses the field observations, physical mechanisms, significant contributing factors, and the design of sand control screens regarding fines migration. The literature gaps in fines migration around thermal wells are identified, and challenges in evaluating wellbore completion's impact on near-wellbore damage by fines migration are determined. In the end, a conceptual framework is developed to reconcile and extend past research on the fines migration issue, particularly on Alberta oil sands.

2.3 Fines Migration in Oil Sands

2.3.1 Fines origin, mineralogy, and size

A generic geological description of oil sands is depicted in **Figure 2.1**, where bitumen is separated from sand or clay particles by a thin layer of water. In low-grade oil sands with high residual water saturation, clusters of silts and clay particles exist within the framework of coarse sand grains [15, 16]. SEM images indicated that clay minerals coat individual sand grains in the Clearwater Formation in the Cold Lake area [17].

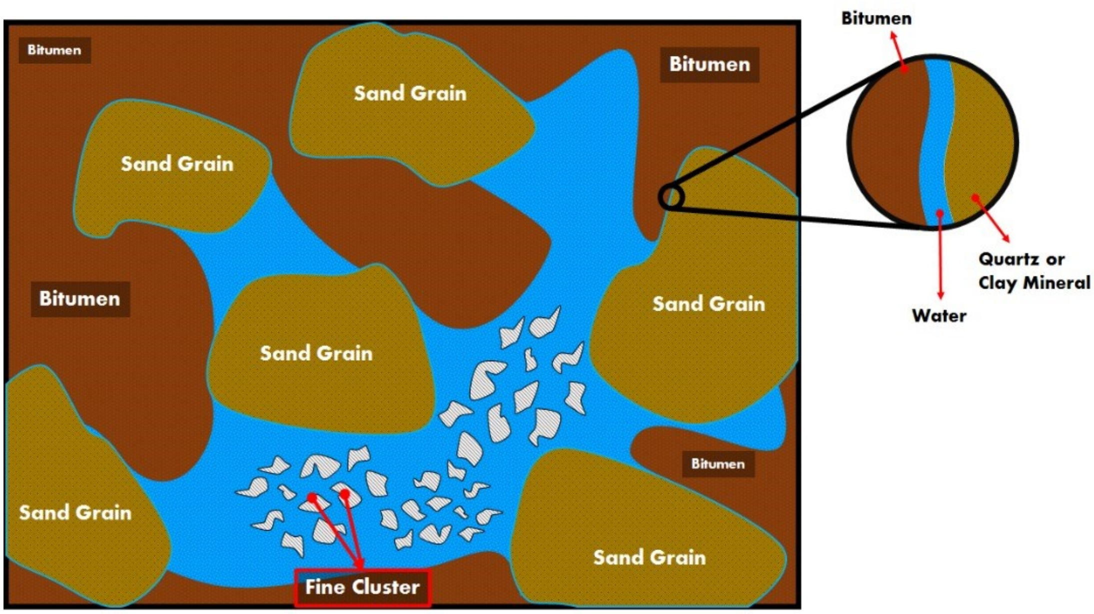


Figure 2. 1: Geological description of Athabasca Oil Sands (Modified after [15])

Alberta oil sands contain a considerable amount of fine particles in the silt size (4-44 µm) and clay size (smaller than 4µm) [4, 18].

The fines may contain clay minerals (such as chlorite, kaolinite, illite, and smectite) and non-clay minerals (such as quartz, silica, feldspar, calcite, and dolomite) [3, 6]. The mineralogical composition of five oil sand deposits in Alberta is shown in **Table 2.1**.

Particle size distribution (PSD) of the McMurray Formation in the Athabasca region has been represented by four PSD categories, with fines content from 5% to 14.5% [4]. Kaolinite and illite are the dominant clay minerals in oil sands [18, 19]. There is no information regarding the percentages of clay and silt minerals for in-situ core samples. Nevertheless, the characterization of an Athabasca oil sand reveals that most, but not all, of the clay minerals are in the clay size fraction [20]. It reveals that non-clay silt-size minerals would also contribute to the fines migration process.

Table 2. 1: Mineralogical description of Alberta oil sands [18]

Oil Sand Deposit		ATHABASCA				PEACE RIVER		WABSCA				COLD LAKE		LL*	
Formation		McMurray		Clearwater		Bluesky/ Gething		Wabiskaw		Grand Rapids		Clearwater/ Grand Rapids		Dina	
Samples		247		15		32		15		6		15		13	
		M	Range	M	Range	M	Range	M	Range	M	Range	M	Range	M	Range
Total Mineral %	Quartz	80	41-97	63	21-87	69	17-92	81	57-96	66	55-87	75	30-98	83	56-95
	Potash Feldspar	2	0-16	6	0-42	2	0-7	4	T-20	10	0-30	7	0-19	3	0-23
	Plagioclase	0.1	0-8	3	0-11	N		1	0-6	12	0-41	7	0-27	2	0-8
	Calcite	0.2	0-28	4	0-12	0.5	0-5	0.9	0-9	0.3	0-2	0.1	0-2	0.1	0-1
	Dolomite	0.4	0-9	4	0-13	5	0-4	1	0-7	N		0.6	0-5	1	0-16
	Siderite	1	0-20	2	0-4	N		0.3	0-2	3	0-15	N		N	
	Pyrite/ Marcasite	0.4	0-10	5	0-45	6	0-62	1	0-4	1	0-8	0.1	0-2	N	
	Kaolinite	9	1-27	5	0-19	15	4-27	7	2-18	4	2-7	3	0-11	6	1-15
	Mica	1	0-8	T	0-2	0.3	0-4	0.8	0-2	0.2	0-1	0.5	0-3	2	0-8
	Illite	4	T-10	6	1-15	3	T-11	3	T-9	3	1-10	3	T-13	2	T-7
	Chlorite	N		0.3	T-4	N		0.1	0-1	N		1	T-7	N	
	Smectite	N		1	T-7	N		N		N		3	0-17	N	
Clay Minerals % (<2 µm)	Kaolinite	65	28-90	39	0-67	85	47-94	74	57-85	54	40-78	52	0-91	67	20-96
	Illite	31	7-54	44	29-66	13	6-35	24	14-38	36	16-60	25	7-42	26	4-60
	Chlorite	0.8	0-18	6	1-15	0.9	0-18	2	0-5	5	0-9	8	2-25	4	0-17
	Smectite	0.2	0-7	11	2-26	0.3	0-3	0.6	0-5	5	0-11	15	0-42	3	0-27
	Mixed-Layer Clays	3	0-26	N		0.7	0-4	N		N		N		N	
	Kaolinite/ Illite Ratio	2	0.2-11	0.9	0-2	7	1-15	3	2-6	2	0.7-5	2	0-9	3	0.6-13
M=Mean, T = Trace, N= Not Detected												*: LLOYDMINSTER AREA			
CSPG© [2020], reprinted by permission of CSPG whose permission is required for further use.															

2.3.2 Field observations of the fines migration

Plugging of slotted liners in SAGD wells has been reported as a common problem [21], which can be attributed to the fouling and scaling of organic and inorganic migratory particles [21, 22]. A high accumulation of fine particles can also cover the sand control slots' openings and plug pore spaces in the near-wellbore region. In some cases, under elevated temperatures and pressure conditions due to fines retention, clay minerals, such as kaolinite, may transform into smectite [22]. Smectite with a swelling behavior may significantly damage the near-wellbore region and reduce wellbore productivity [10].

Williamson et al. [23] published field observations of two pilot SAGD well pairs in the Lower Grand Rapids (LGR) Formation of the Cold Lake/Lloydminster area. The petrographic analysis showed that the LGR Formation contains less than 5% fines and non-swelling clays. The producers of the first and second SAGD well pairs were completed with slotted liner (SL) and wire-wrapped screen (WWS), respectively. After eight months of steady oil production, the differential pressure between injector and producer of the first well pair started increasing to above 1000 kPa, and the production rate was reduced. The initial treatment program, as acid stimulation, showed marginal and short-term improvement compared with the subsequent treatment (perforation job) with significant and long-lasting results. The perforation job treatment resulted in lower differential pressure below 100 kPa. In contrast, the second well pair had stable differential pressures over its lifetime and delivered higher production rates showing that WWS had better sand control performance.

For the first SAGD well pair, Williamson et al. [23] combined operational data with petrographic properties (XRD, SEM) of core samples obtained before steam injection and after perforation job (post steam). They concluded that the near-wellbore was initially damaged by fine particles (mostly kaolinite), and later, mineral transformation under high temperature and pressure conditions caused additional well impairment. It was believed that a fast ramp-up by the electrical submersible pump (ESP) generated a high influx, which mobilized the fine particles toward the slotted liner and plugged the pore spaces near the wellbore. This plugging intensified the interstitial velocity of flowing emulsion and caused a further release of fine particles. Besides, the petrographic results showed the presence of smectite as a swelling clay in the post-steam core samples, indicating mineral transformation [23].

Romanova [22] analyzed the plugging materials of a slotted liner recovered from a well in the McMurray Formation (Long Lake area). The results showed that the primary plugging materials were composed of clay-sized particles (mostly kaolinite) combined with the corrosion products.

2.3.3 Fines migration in coreflooding experiments

Few works have been published on laboratory study of fines migration in Alberta oil sands through coreflood experiments on core samples. Permeability variations on core samples from Cold Lake oil sands were determined by establishing single-phase bitumen flow, resulting in an unexpected decrease in permeability [17]. At the beginning of the test, the absolute permeability of 1100 mD dropped to 234 mD after flooding the core with heavy oil at high temperatures (up to 149ºC). The absolute permeability in single-phase heavy oil flow, 580 mD at 66ºC, also dropped to 175 mD when the core was heated to 149ºC for one day. XRD and SEM images of samples were taken from the core's inlet and outlet and compared with the initial oil sands to investigate the causes of permeability drop. It was observed that clays coating the sand grains detached from the inlet and plugged the pore throats near the outlet. The detachment mechanism was likely attributed to weakening the bonding forces between the sand grains and clay coatings at a higher temperature of 149ºC [17].

Kwan et al. [24] performed a series of tests on preserved and repacked core samples of Cold Lake oil sands and confirmed the permeability impairment by fines migration. The tests were conducted at different salinity, flow velocity, and flow reversal conditions. The results showed that preserved core samples had much higher initial permeability than repacked samples due to particle redistribution. In all experiments, the permeability was reduced when both 2% NaCl brine and distilled water were injected, or the flow rate was increased. However, the reduced permeabilities were much lower for preserved samples having high initial permeability. The permeability reduction was attributed to fines migration and plugging of pore throats in the flow direction. It was also found that reversing the flow direction and injection of Methylene Chloride could partially recover the impaired permeability. **Figure 2.2** shows the permeability variations during test stages for a preserved core sample.

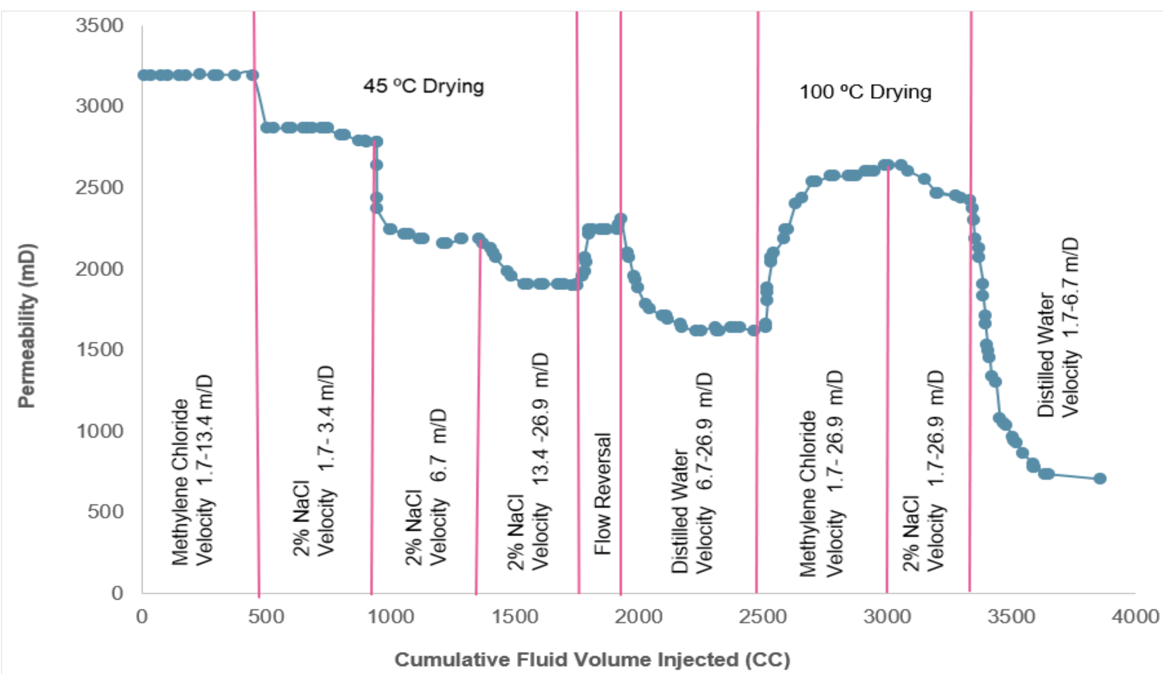


Figure 2. 2: Permeability variations of a preserved oil sand sample in different flow conditions [24].

2.4 Influential Factors in Fines Migration Process

Table 2.2 summarizes the influential factors in five categories: (1) porous medium-related factors, (2) carrier fluid-related factors, (3) environmental factors (temperature), (4) well operating-related factors, and (5) well completion factors. Some factors are generic, and others are specific to thermal operation in unconsolidated oil sands. The effect of these factors has been investigated through many coreflood experimental tests, especially on homogenous Berea sandstone cores [3,25-31]. A few flow tests have also been conducted on unconsolidated sand packs using synthetic or natural sands [3,25,27,32-34]. The tests included various scenarios such as piecewise flow rate increase, gradual salinity decrease, single-phase and multi-phase flow with polar oil, non-polar oil, and solvents. The fines migration was measured by monitoring effluent fines production and permeability variations in the core plugs and sand packs [10, 25].

Table 2. 2: Factors influencing fines migration process in porous media [6,9,10,30,35,36].

Category	Influencing Factors
Porous medium-related factors	Pore and particle size distributions, compaction, oil sand evolution around the wellbore, formation fines content and mineralogy, grains' and fines' wettabilities
Carrier fluid-related factors	Brine salinity, brine pH, composition (salt type, the valency of ions), multi-phase flow conditions (water cut, steam-breakthrough, emulsion)
Environmental factors	Temperature
Well operating factors	Wellbore flow rate (flow velocity), production ramp-up
Well completion factors	Sand control device characteristics (type, aperture size, open to flow area)

2.5.1 Porous medium-related factors

2.5.1.1 Pore and particle size distribution

The size distributions of particles and pores play an essential role in the migration of fine particles and retention processes. Large-sized particles would be released by lower drag forces and captured in a narrow pore throat by a mechanism known as size exclusion or straining. This mechanism takes place below a critical pore throat to particle diameter ratio. Several small particles can form a bridge at the pore throat entrance when simultaneously approaching a pore throat due to hydrodynamic effects [37].

Conventionally, one-third, one-seventh, and one-fourteenth rules of thumb were proposed for the transportation and retention of fine particles in porous media [35, 38]. These rules state that:

- Fine particles larger than 1/3 of the mean pore size can bridge at pore throats,

- Fine particles smaller than 1/3 but larger than 1/7 of mean pore size deposit at pore surfaces, form bridges at pore throats and reduce effective pore/pore throat size,
- Fine particles smaller than 1/7 but larger than 1/14 of mean pore size deposit at pore surfaces and reduce effective pore size when the effect of gravitational force is significant compared with the drag force
- Fine particles smaller than 1/14 of the mean pore size pass through the pores and cause no damage.

However, many experimental results contradict the above rules due to the porous media's complex nature [38].

The average pore diameter, pore throat size, and the pore body to the pore throat size ratio depend on several factors, including the depositional history, grain size, grain geometry, fines content, and compaction level of the formation. Several methods have been suggested to calculate the mean pore/pore throat size based on particle (grain) size distribution (PSD), permeability, and porosity [39-44].

Abram and Cain [4] classified the McMurray Formation oil sands into four representative PSD classes **(Figure 2.3)**. DC-I is the finest PSD with the highest fines content of 14.5% (3% clay). Classes DC-II, DC-III, and DC-IV have fines content of 7.4%, 5.4%, and 4.2%, respectively [4]. According to the one-third rule of thumb mentioned above, plugging particle sizes of 3.6-16.8 microns and 4.1-19 microns have been stated for Class II and Class III, respectively [35].

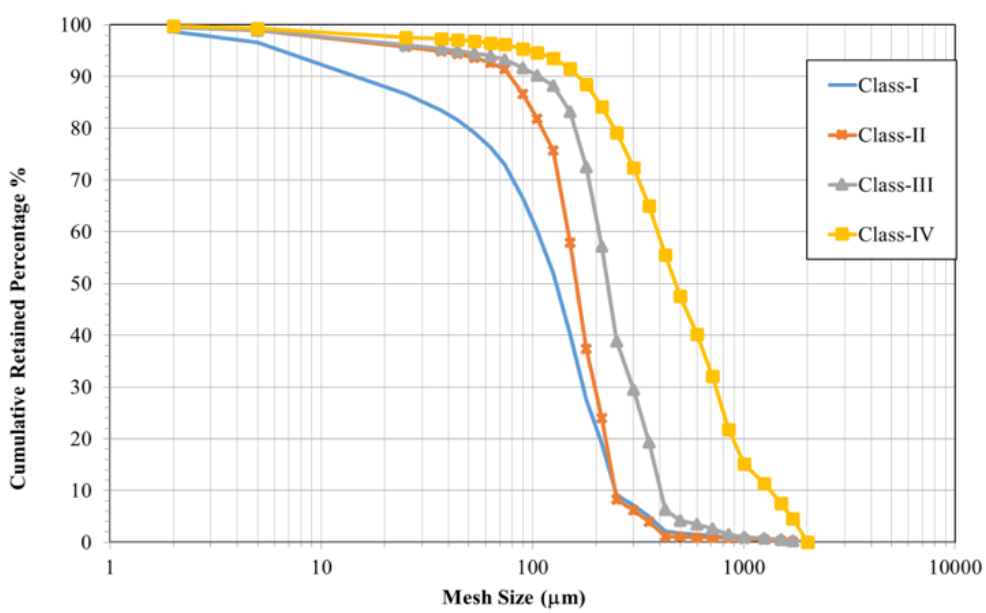


Figure 2. 3: PSD of the representative classes of oil sand in McMurray Formation [4].

2.5.1.2 Compaction

The compaction of the reservoir sands changes as the effective stresses evolve; hence, the pore structure is altered. It has been observed that the critical velocity to mobilize fine particles in a core sample from Grand Rapids Formation in the Cold Lake area decreased as the effective stress increased [45]. A few recent works also investigated the stress effect on fines migration and permeability impairment in an unconsolidated sample with a PSD similar to McMurray Formation [46, 47]. The results indicate that higher effective stress leads to less sand production but higher plugging and permeability reduction due to fines migration.

2.5.1.3 Oil sand evolution around the wellbore

In SAGD wells, there is typically a gap between the formation and sand control screen after the screen installation. Because of the unconsolidated nature of the oil sands and bitumen melting during the pre-heating phase, the sand collapses around the liner, hence developing a high-porosity high-permeability zone with low effective stress [35, 48]. During the steam injection phase and the steam chamber expansion, the effective stress builds up and causes gradual compaction of the collapsed zone [35, 36, 49]. Factors such as in-situ stresses, thermal expansion, and shear dilations influence effective stress around the liner [49]. The gradual effective stress build-up around the screen results in smaller pore sizes and higher interstitial velocities, which favor fines detachment and plugging tendency in narrow pore throats.

2.5.1.4 Fines characteristics

2.5.1.4.1 Fines mineralogy

The mobilization and retention of fine particles are also affected by the mineral composition and fraction of mobile fine particles within porous media. Fine particles may include non-clay and clay mineral particles (charged or uncharged) and show different colloidal behavior in contact with saline water. Smectite swells six to ten times its original volume and restricts fluid flow in the pore space [50]. Kaolinite and illite, which are the primary migratory clay minerals in oil sands, may disperse in low salinity brine, fill pore bodies, or bridge the pore throats [50]. The dispersion of clay materials is controlled by their cation exchange capacity (CEC); higher brine salinity is required to disperse the clay minerals with a higher CEC value. The CEC values of smectite, illite, and kaolinite clays are in the range of 80-150, 10-40, and 2-5 meq/100 g, respectively [16].

2.5.1.4.2 Fines content

Higher fines content increases pore and screen plugging tendency in SAGD production wells. Sand control design in formations with more than 15% fines content has proved problematic due to fines migration [50]. Sand retention testing (SRT) results with a single-slot slotted liner coupon also showed severe plugging tendency in the sand pack with high clay content (kaolinite and illite) [21].

Russell et al. [11] conducted systematic experimental research on unconsolidated sand samples to investigate the effect of kaolinite content on permeability damage during a step-wise decreasing salinity level. Results showed higher permeability reductions for the higher kaolinite content, justified by a high concentration of dispersed kaolinite particles in the carrier fluid, which increased the pore throats plugging.

2.5.1.4.3 Wettability

The wettability of the formation fines affects their transport in the porous media. Mucke [3] found that fine particles tend to move with the wetting fluid phase. Clay particles are usually water wet and tend to flow when water is being injected or produced [3]. Mixed-wet fine particles move along the interface of two-phase flowing fluid through the porous media [3].

Investigations of various wettability combinations (water-wet rock/water-wet fines; water-wet rock/oil-wet fines; oil-wet rock/water-wet fines; oil-wet rock/oil-wet fines) through the flooding of sandstone cores with fines suspension showed more reduction of porosity and permeability when the rock and fines had the same wettability [51]. In this case, fines plugged the thin pore throats and filled the adjacent pore spaces. However, minimal damage has been observed when fine particles and rock core plugs had different wettability [51].

The widely accepted structural model developed for Alberta oil sands indicates the water-wet behavior of sand grains, including a water film around them as an interface between grains and bitumen [15]. Fine particles usually cover the sand grains, and in some cases, clusters of fine particles saturated with water may exist [15].

2.5.2 Carrier fluid-related factors

2.5.2.1 Salinity and pH

Some brine characteristics as carrier fluid of fine particles in the reservoir, including salinity, pH, and composition, significantly impact the fines migration process. At low salinity, high pH, and the presence of monovalent cations, the net electrical interaction between fine particles and grains becomes repulsive (high zeta potential), and fines are detached from the pore surfaces [52, 53].

Experimental works performed by Khilar and Fogler [28] introduced the critical salt concentration (CSC) as a certain salinity level below which fine particles are released and stay suspended. For a NaCl brine system in consolidated cores of Berea Formation, CSC values of 0.07 M, 0.03 M, and 0.004 M, corresponding to pH values of 8, 8.5, and 9.5 were detected [54]. It was found that a CSC exists only for monovalent cations. Brines with bivalent and trivalent cations have no remarkable effect on fines migration. Different monovalent cations have different impacts on the dispersion or release of fine particles in low salinity brine. An order of Li^{+}=Na^{+} > K^{+} > NH^{+}_{4} > CS^{+} was observed [54].

The H^{+} ion, as a monovalent cation, has a reverse effect on the dispersion behavior of the charged particles. At high pH values, the zeta potential becomes highly negative, which results in a significant repulsive force causing the release of fine particles [30]. Exposing a brine-saturated core (0.51M NaCl) to the freshwater at pH 2.0 did not result in a decline in permeability. Little change in permeability was observed for pH up to 9.0 [30]. However, a rapid and considerable decrease in permeability was observed at pH>11.0.

Several publications confirmed that the rate of salinity changes has more effect on the release of fine particles than the absolute salinity [26, 30, 54]. A continuous versus abrupt salinity decrease led to less permeability damage. It was attributed to a log-jam effect where a high concentration of released particles in a sudden salinity decrease could significantly plug the pore throats [30].

In the SAGD oil recovery process, the condensate water at the steam chamber's edge is expected to combine with high-saline formation water. Therefore, relatively low salinity water is produced from the liquid pool associated with bitumen emulsion. Salinities in the range of 400 ppm to 3400 ppm of NaCl brine and pH values from 7.1 to 8.8 have been reported for produced water at different SAGD projects [53]. A gradual increase in pH level is expected when steam is injected with an alkaline liquid residual of the boiler feed [2]. These low salinities associated with high pH values in SAGD operations would promote the repulsive surface forces and release fine particles near-wellbore regions. The results of the investigations into the effect of salinity and pH on permeability damage of pre-pack samples representing McMurray Formation showed a good agreement with the theory of clay dispersion in interaction with saline water [53, 55].

2.5.2.2 Multi-phase flow conditions (water cut, steam breakthrough, emulsification)

Muecke [3] combined micromodel and linear flow studies to understand the fines migration process. He performed a series of single-phase and multi-phase linear flow tests in a large-scale sand pack (122cm in length, 3.81cm in diameter) to verify visual observations from their micromodel. The two-phase flow of oil and water with migrating fines toward the SAGD producer is simulated in the micromodel, as depicted in **Figure 2.4**. Results showed that mobilized fine particles could establish mechanical bridges at pore restrictions.

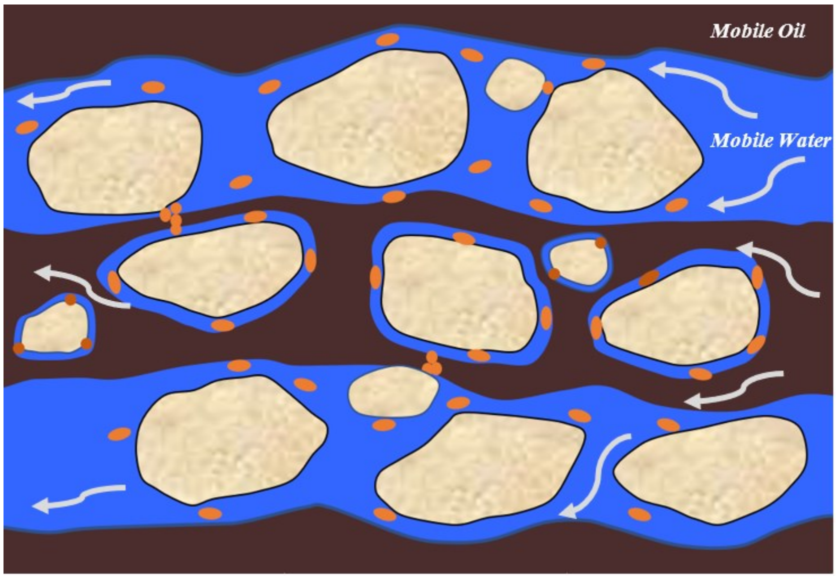


Figure 2. 4: Fines migration with the simultaneous oil and water flow (Modified after [3]).

Muecke [3] also found that fine particles moved only with the wetting phase, and in multi-phase conditions, higher water cut would result in higher fines migration. Thus, in the SAGD process, with the simultaneous two-phase flow of condensate water and melted bitumen, water-wet fine particles move with mobile water. Two-phase flow tests in unconsolidated pre-pack samples with clay particles showed higher plugging and fines production than single-phase flow tests with a non-wetting phase (oil). The testing results also showed that fines mobilization and migration are more substantial in higher water cut levels [21,49,56-58]. Three-phase flow (oil, water, and gas) resulted in the highest plugging and fines production [56, 57]. The three-phase flow test with gas injection resembles the live steam breakthrough in some SAGD producer segments. Although an operating steam-trap or subcool control is used to prevent the steam breakthrough, some intervals still may experience steam production due to reservoir heterogeneity and wellbore trajectory excursions.

The produced melted bitumen in the SAGD recovery has been reported as water-in-oil (W/O) emulation [59]. Studies showed that the W/O emulsion in the SAGD process has a higher viscosity than the oil [59]. Although there is no experimental work investigating the effect of emulsion flow on the fines migration process in unconsolidated oil sands, it appears higher emulsion flow viscosity may have a noticeable effect in displacing the fine particles due to the higher viscosity and drag.

2.5.3 Environmental factors (Temperature)

Experimental studies showed that increasing the temperature reduces the permeability due to the fine particles mobilization [28, 60] and fines release [61], which affect the concentration of attached particles [52, 62, 63]. It was observed that permeability was reduced to 69% when the temperature changed from 21.1°C to 162.8°C [60]. The rate of permeability damage of Berea sandstone cores reduced when the temperature was lowered [28]. Regarding the colloidal behavior theory, the repulsive electrical forces are more potent at higher temperatures, boosting the release of fines from pore surfaces and consequent permeability reduction [61].

More interesting results related to the effect of temperature and salinity on the permeability of sandstone cores were reported by Rosenbrand et al. [46]. It was found that the impact of salinity on permeability damage is different at 20°C and 80°C. Decreasing the salinity at 80°C had an insignificant influence on the already reduced permeability by temperature. In contrast to the salinity effect, the permeability reduction due to heating could be significantly restored by cooling the sample. This behavior was explained by the strong repulsive grain-particle and particle-particle interactions at 80°C. Here, the released particles do not form large aggregates and plug the pore throats or bridge at pore throats. The dispersed particles possibly form a suspension of interacting particles as a porous network in the pore bodies [46]. Thus, the permeability is reduced as the effective specific surface area for flow is increased by the porous network. This mechanism could be confirmed by the reversible effect of flow velocity on permeability variation in high-temperature experiments and no fines production during the flow test. Here, higher flow velocities could shear the suspended fine particles and increase the permeability. By cooling the sample, fine particles reattach to the pore surfaces and significantly restore the permeability [46].

Schembre and Kovscek [61] showed permeability reduction in a Berea sandstone core with no fines mobilization at temperature levels up to 120°C while flowing brine with pH of between 7 and 10 and salinities of 0.01M to 0.05M. However, in the temperature range of 120°C to 180°C, more reductions in permeability and fines production were observed, indicating the transportation and straining of the released fines at pore throats [61].

Typical downhole temperatures for a SAGD producer well are in the range of 200°C to 230°C. The release and migration of fine particles are more likely at high-temperature SAGD conditions.

2.5.4 Well operating factors

2.5.4.1 Wellbore flow rate (flow velocity)

Laboratory investigations show that fines could be mobilized and migrated due to excessive drag forces from the high flow rates, even in the high-salinity brine injection [25, 26]. Gruesbeck and Collins [25] confirmed the existence of a critical flow velocity above which the entrainment of fine particles occurs and changes the porous medium's permeability. A critical velocity of about 25 cm/hr was reported for consolidated cores of Berea sandstone when the core sample was flooded with 2% KCl brine [25, 27]. However, later experimental tests showed much higher critical velocities in the range of 2000-5000 cm/hr for Berea sandstone cores even when the core was flooded with low salinity (0.035%) NaCl brine [26]. This difference can be justified by the much lower initial permeability (about 50 mD) of core samples in the former experiments [25]. The lower initial permeability of the core sample in a test with a constant injection rate can generate higher shear stress or drag forces, which accelerate the release of fine particles.

The permeability decrease with low salinity was more significant than with high salinity when the flow rate increased [26]. This phenomenon is justified by the high concentration of released particles in low salinity conditions, which increases the possibility of permeability damage. It was concluded that the concentration of released particles by the hydrodynamic effect is less than that by the colloidal effect [26]. The pore throat plugging is the major mechanism responsible for permeability damage where the concentration of released fine particles is low. In this case, the permeability rapidly drops and then becomes stable. However, other capture mechanisms such as surface attachment, sedimentation, and direct interception may simultaneously occur with high mobile fines concentration. These mechanisms lead to a significant decrease in permeability at earlier stages and a continuous reduction at later times [26].

For typical SAGD production rates of a horizontal wellbore, up to 4500 bbl/day [64], the near-wellbore flow velocities are not expected to be high enough to destabilize the fine particles. However, due to the wellbore's nonuniformity, some sections may experience high local velocities (i.e., high drag force) that trigger the release of fine particles near the wellbore. A sand control screen with a limited open flow area would amplify the release process by flow convergence and impact the near-wellbore retention concentration of fine particles.

2.5.4.2 Production ramp-up

SAGD wells may experience aggressive production ramp-ups following wellbore interventions. High-pressure gradients would be generated in this situation, causing the fines migration process over a finite time [35]. The rate of velocity increase (or ramp-up rate) also influences fine particles' release from pore surfaces. Local variations in pressure or flow velocity cause a spontaneous release process, while sudden bulk variations initiate a provoked release process everywhere in the whole medium [7]. From the experimental works, Gruesbeck and Collins [25] found that an abrupt change in bulk flow velocity can develop turbulent eddies due to pressure disturbances, which enhance drag force on fine particles and their mobilization. This effect is evident in the tests by a sharp increase in effluent fines production [25]. Nevertheless, in low flow velocities less than critical velocity, the low concentration of released particles due to an abrupt change in velocity does not significantly change the permeability [27].

2.5.5 Well completion factors

Standalone screens such as slotted liners (SL), wire-wrapped screens (WWS), and punched screens (PS) have been widely employed in horizontal SAGD wells [56, 58]. Slotted liners (SL) are popular for their low manufacturing costs and adequate mechanical integrity when running into long horizontal SAGD wells [21,64-66]. The other options are preferable for formations with severe plugging issues [65-68]. The SL specifications include slot width, slot length, slot density (number of slots per foot of pipe), and slot patterns **(Figure 2.5)**, which result in an open flow area (OFA) in the range of 1-6% [64, 68]. Slot width and slot density are two critical factors influencing sand control and flow performance.

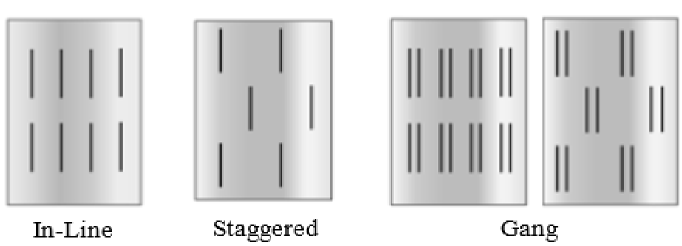


Figure 2. 5: Slotted liner with different slot patterns [69].

In many SAGD applications, the screen has successfully minimized sand production, but they have often failed in managing the mobilized fines near the wellbore [19, 23, 50]. Permeability damage due to the fines migration process creates high differential pressures between the injector and producer wells. Such pressure drops have been observed after several, only a few months of production [23].

Pre-packed sand retention tests (SRT) using a scaled or full-scale screen coupon are usually conducted to evaluate the screen performance and establish the design criteria under representative SAGD wells conditions [64, 68]. Table 3 summarizes the testing variables of some recently published papers evaluating the screen's performance by the SRT equipment.

Table 2. 3: Specifications of recent SRTs evaluating retained and produced fine particles for SAGD applications.

Reference	SCD Type	Aperture Size (inch)	Slot density	Axial stress (psi)	Fluid Flow			
					Fluid type	Salinity (ppm)	pH	Flow rate (bbl/d)*
Mahmoudi et al. [35]	SL	0.01,0.014, 0.018,0.022, 0.026	30,42,54	2	Brine	0, 7000, 14000	6.9, 7.9, 8.8	1500-12000
Wang et al. [71]	SL	014, 0.018,0.022, 0.026	30,42,54	60	Brine	7000	7.9	1800-11000
Fattahpour et al. [36]	SL	0.014	54	0, 300,500,700	Brine	7000	7.9	2000
Montero et al. [57]	WWS	0.06,0.010, 0.014,0.018, 0.022	NA	60	Brine, Mineral oil, Nitrogen	400	7.9	4000-20000
Guo et al. [58]	SL	0.014, 0.026	30,54	0, 300	Brine	7000	7.9	2000
Wang et al. [56]	SL, WWS, PS	0.014, 0.18	54	60	Brine, Mineral oil, Nitrogen	400	7.9	4000-20000
Haftani et al. [53]	SL	0.014	42	2	Brine	7000,2600, 400,100,50, 0	7.5	4000-26000
Wang et al. [72]	SL	0.014	42	25, 400, 500, 700 (Lateral 25, 300)	Brine, Mineral oil, Nitrogen	7000	7.9	2500

Remarks:
PSD: McMurray Formation (Porosity: 0.29-0.35 ; Permeability: 1-3 Darcy)
Fines content: 5 w%, 7 w%, 14.5 w%
Sample diameter: 6 in
Sample length: 13.5 in, 16.5 in
Outlet pressure: 2 psi
Temperature: Room temperature (20°C)
*: Lower bond values are equivalent to typical flow rates for a SAGD well with 800 m horizontal length completed with a 7 in diameter SCD
SL: Slotted liner, WWS: Wire-Wrapped Screen, PS: Punch Screen

The screen sanding and plugging performance can be quantified by sand retention tests by measuring the total amount of the produced sand and the retained permeability. The latter is defined as the permeability of the combined screen and sand pack near the device relative to the initial permeability [64, 70]. Therefore, the retained permeability accounts for the extent of permeability reduction by fouling/fines materials covering the screen slots (screen plugging) and fines accumulation in the sand next to the screen (pore plugging) [13, 70]. The latter is caused by the organic and inorganic scaling as well as the fines migration process.

The sand retention tests provide data regarding the concentration of produced fines during the test and fines concentration at different sample intervals after the test completion. While the testing design does not fully capture the reservoir conditions (e.g., pressure and temperature), the results allow the relative comparison of different coupons. Coupons with smaller slot sizes (or aperture size) and lower slot densities result in higher fines retention near the coupon, thus lower retained permeability [58,73]. A comparison of different tests indicates that the effect of aperture size is more significant than slot density [58]. WWS coupons with the same aperture size as SL and PS exhibit the highest retained permeability due to the higher OFA [56, 57]. Some tests have been carried out to assess the impacts of multi-phase flow, pH, salinity, and stress on fines migration. High water cuts and three-phase flow with nitrogen are seen to cause higher levels of fines migration and permeability impairment [56,57,72]. Some observations indicate an increase in permeability due to the disruption of plugging bridges by turbulence effects of multi-phase flow [3, 21]. In addition to the testing procedure, the current SRTs have several limitations concerning radial flow geometry toward the screen, high-pressure and high-temperature conditions, and the use of natural unconsolidated sands and reservoir fluids.

2.5 Mathematical Modeling of Fines Migration Process

Mathematical modeling of the fines migration process within porous media allows predicting the near-wellbore permeability changes and wellbore productivity. The modeling also facilitates sensitivity analysis to assess the significance of contributing factors. Laboratory modeling is still necessary to calibrate and validate the mathematical model.

Traditionally, colloidal particles are species between 0.001 and 1 micron and suspended particles with sizes larger than 1 micron [74-76]. The flow of natural fines in porous media can be thought of as a suspension transport problem in which physiochemical (surface forces) and mechanical forces intervene [7]. Therefore, in contrast to colloidal transport, the effect of intermolecular forces or diffusion is not significant [7].

Both macroscopic and microscopic models have been applied to describe formation damage due to mobilization, transportation, and retention of the fine particles. Microscale models include population balance models, random walk equations, and direct pore-scale simulation, which account for pore size distribution and pore level heterogeneities of porous media [8.77-79]. The macroscopic models are based on continuum mechanics principles, where the material's behavior is averaged over a continuous mass rather than calculated for discrete particles. The macroscopic models predict the macroscopic distribution of the migrating particles (affecting the average porosity) and the extent of permeability variation. The microscopic physics and macroscopic equations describing the fines migration process within porous media are reviewed in the following sections.

2.5.1 Microscopic view

2.5.1.1 Physics of Fines Release

Figure 2.6 shows the schematic of forces acting on fine particles, including hydrodynamic forces (drag and lift), surface forces (electrical forces), and gravitational force. Electrical force includes attractive Van der Waals (F_{VDW}), repulsive Electrical-Double-Layer (F_{EDL}) and Born repulsive (F_{BRN}) forces. Fine particles can detach from rock surfaces when net repulsive forces or torques acting on particles overcome the particles' primary mechanical equilibrium [9-11,26,52,80].

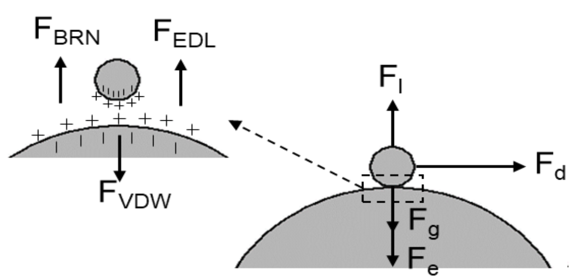


Figure 2. 6: Schematics of forces acting on fine particles attached to the grain surfaces.

The drag force (F_d) is expressed as a function of fluid velocity (u), fluid viscosity (μ), mean fine particles radius (r_f), mean pore radius (r_p) and a dimensionless drag coefficient (ω) [11]:

$$F_d = \frac{\omega\pi\mu\, {r_f}^2\, u}{r_p} \tag{1}$$

The significance of lifting (F_l) and gravitational (F_g) forces are negligible compared with electrostatic and drag forces with fluid flow in porous media [11, 52, 81, 82]. Theoretical and experimental studies show that hydrodynamic forces are significant when the flow velocity is high enough (in order of 10^{-3} m/s), a condition that is often met near the wellbore [2].

The electrostatic force (F_e) is calculated based on electrostatic interaction energy between fine particles and grains, as described by the DLVO (Derjaguin-Landau-Verwey-Overbeek) theory. The total interaction energy (V) is the summation of London-Van der Waals (V_{LVW}), Electrical-Double-Layer (V_{EDL}) and Born repulsive (V_{BR}) energy potentials [9, 11, 74]:

$$V = V_{LVW} + V_{EDL} + V_{BR} \tag{2}$$

$$V_{LVW} = -\frac{A_{123} r_f}{6h}\left[1 - \frac{5.23h}{\lambda_w} ln\left(1 + \frac{\lambda_w}{5.23h}\right)\right] \tag{3}$$

$$V_{EDL} = \frac{128\,\pi\, r_f\, n_\infty k_B T \psi_f \psi_g}{k^2}\; e^{-kh} \tag{4}$$

$$V_{BR} = \frac{A_{123}\,{\sigma_c}^6}{7560}\left[\frac{8r_f + h}{\left(2r_f + h\right)^7} + \frac{6r_f - h}{h^7}\right] \tag{5}$$

where h is the fine particles-grains separation distance, A_{123} is the Hamaker constant, λ_w is the characteristic wavelength of interaction, n_∞ is the bulk number density of ions, k_B is Boltzmann constant, T is the temperature in Kelvin, k is the Debye-Huckel parameter, σ_c is the atomic collision diameter, ψ_f and ψ_g are the surface potentials of fine particles and grains, respectively.

The electrolyte solution as the permeating fluid in porous media develops an electrical double layer around charged (usually negative) solid surfaces of grains and fine particles **(Figure 2.7)**. The outer layer, known as the diffusive layer, is rich in ions with opposite charges and moves with the solid. The diffusive layer's thickness depends on electrolyte solution properties, including salinity, the valence of cations in solution, pH, and temperature. The electrical potential at the boundary between the diffuse layer and solution is known as the Zeta potential [7]. The V_{EDL} is the net repulsive interaction between double layers of fine particles and grains.

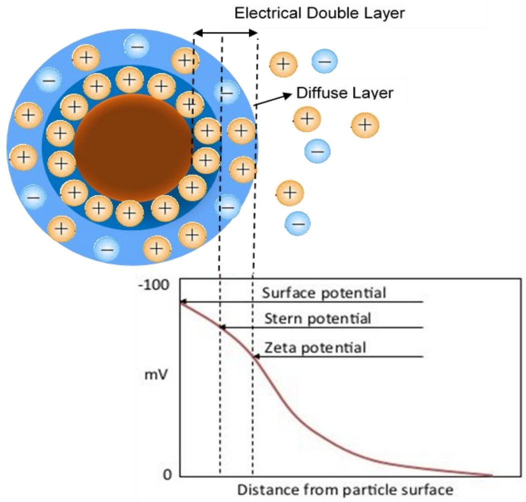


Figure 2. 7: Electrical double-layer demonstration.

The surface potentials ψ_f and ψ_g are estimated based on the Zeta potentials as follows [11, 74]:

$$\psi_{f,g} = \tanh\left(\frac{ze\zeta_{f,g}}{4k_BT}\right) \tag{6}$$

where, $\zeta_{f,g}$ is the zeta potential of fine particles and grains individually, z is the valance of cations in solution, and e is the elementary charge (1.602×10^{-19} C).

By defining the total electrical potential, the electrostatic force (F_e) is quantified as the negative gradient of electrical potential concerning the separation distance between solid surfaces [11].

$$F_e = -\frac{\partial V}{\partial h} \tag{7}$$

Generally, where the zeta potential values positivity is greater than +30 mV and negativity is lower than −30 mV **(Figure 2.8)**, the net electrostatic force is repulsive. Thus, fine particles tend to detach from the pore walls (grain surfaces) or separate from the surrounding particles [83]. In this circumstance, the dispersion resists aggregation and flocculation of particles. Therefore, depending on particle-particle and particle-grain interaction energies, different mechanisms of dispersion and flocculation are possible.

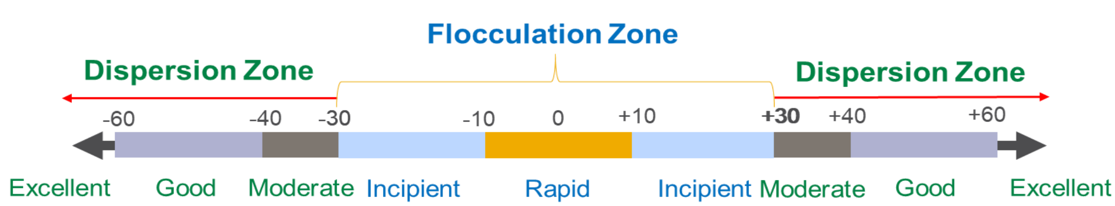


Figure 2. 8: Variation of the zeta potential and charged particle behavior.

In most modeling cases, it is assumed that the release mechanism does not significantly affect permeability increase, and they only account for permeability decrease due to retention mechanisms [9, 11, 52, 63]. At high temperatures and low shear rates, the release of stacked platelet-shaped particles such as kaolinite clays establishes a suspension that increases the effective surface area and resists the flow in a pore, thus decreasing permeability [46].

2.5.1.2 Physics of Fines Retention

It is essential to know the microscopic pattern of retained fine particles as the basis for clogging models, which strongly controls the capability to predict the extent of formation damage. The retention's primary impact is to occupy a part of the space earlier available to flow, reducing the average porosity of the porous medium.

Several retention mechanisms bring migrating particles into contact with retention sites such as pore surfaces, pore throats, and dead-end (crevice and cavern) spaces [7]. The fundamental retention mechanisms, as depicted in **Figure 2.9**, include size exclusion, mechanical and hydrodynamic bridging, surface deposition, sedimentation, direct interception, inertial impaction, sorption, and Brownian diffusion [7,12,26,37,84-88]. In the case of fine particle migration within porous media, the retention of fine particles in pore throats significantly damages the permeability.

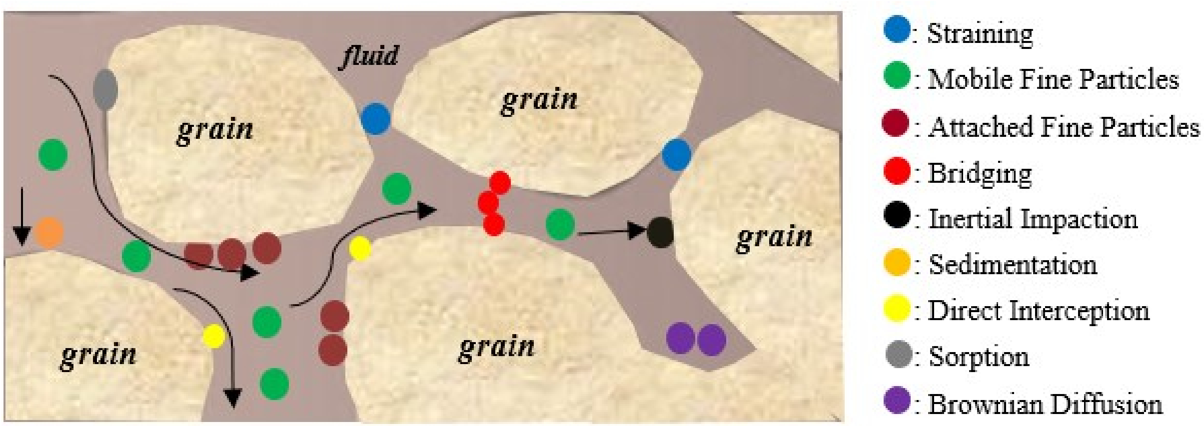


Figure 2. 9: Different mechanisms of particle retention in porous media.

In addition to forces acting on a fine particle attached to pore surfaces, a moving particle within a carrier fluid also experiences inertial forces. Inertial forces effect is significant in high and spatially varying velocities by radial flow around the SAGD well, converging toward the screen openings [12]. In such conditions, fine particles tend to maintain their trajectory where flow streamlines suddenly change in the completion zone. Consequently, particles are more likely to deviate from the flow streamlines, impact the pore walls, and retard in the completion zone [12]. This mechanism, known as inertial retardation or inertial impaction, leads to a gradual accumulation of fine particles on pore spaces and pore throats in the restriction zone [12]. In another condition, the screen can discharge the retained particles on pore walls over time, and the reduced retained permeability of the completion zone is recovered [13]. The macroscopic modeling should account for this behavior by incorporating appropriate kinetics for the retention and release of fine particles.

2.5.2 Macroscopic View

Continuum models can be employed to predict the macroscopic distribution of migrating and retained particles to estimate the permeability variation. The location and extent of fines deposition are deemed consequences of the interplay between convective, diffusive, release, and retention fluxes. These interactions are described by a convection-dispersion equation described by Equation (9). The governing equations describing the fines migration process in porous media at single-phase flow conditions consist of several equations. These equations are momentum (Darcy's law) equation, mass balance equations for water and mobile particles (Equations 8, 9), kinetic equations for release and plugging rates, porosity variation equation, and an empirical expression for permeability variation.

$$\frac{\partial[\varphi\ (1-C_m)\ \rho_w]}{\partial t}+\nabla\cdot[(1-C_m)U\ \rho_w]=0 \quad , \ U=\ \frac{K}{\mu}\nabla P \tag{8}$$

$$\frac{\partial\left(\varphi\ C_m+\sigma_a+\sigma_p\right)}{\partial t}+\nabla\cdot(U_s\ C_m-D\ \nabla C_m)=0 \quad , \ U_s=\alpha\ U \tag{9}$$

where, C_m is mobile fines concentration [volume/pore volume], σ_a is the concentration of fine particles attached to pore surfaces [volume/bulk volume], σ_p is the concentration of fine particles plugged in pore throats [volume/bulk volume], φ is the instantaneous porosity of the medium, D is dispersion coefficient, U is Darcy velocity, and α is drift delay factor. The terms $(\partial\sigma_p/\partial t)$ and $(\partial\sigma_a/\partial t)$ account for the kinetics of pore throat plugging and pore surface attachment mechanisms, respectively. More precisely, $(\partial\sigma_a/\partial t)$ reflects the net rate of attachment of fine particles to the pore surfaces, considering the release and reattachment mechanisms. The concentration of retained particles at pore throats is responsible for high-pressure drops and permeability reduction during the process. Usually, the relative variation of permeability to the initial permeability is expressed as a function of release and retained particle concentrations by an empirical equation [9, 11, 34].

Numerous researchers introduced different empirical kinetic equations accounting for the rate of release and retention of fine particles on pore surfaces and pore throats due to hydrodynamic and chemical effects [7-9,14,25,89-92]. **Tables 2.4** and **2.5** summarize the most critical mechanisms of the fines migration process as the kinetic equations for pore surface release and pore throat plugging mechanisms, respectively.

According to the kinetics equations, the release rate is proportional to the difference between the current and critical values of driving forces depending on velocity and salinity. Moreover, the plugging rate is proportional to convective flux ($U\, C_m$) of mobile fine particles. Most of the plugging rate equations also account for the effect of accumulation of fine particles behind the previously plugged particles by considering a term ($\lambda_b\ \varphi$ or $\lambda_b\ \sigma_p$) as a linear function of porosity or plugging fines concentration.

Civan [14] provided an excellent theoretical explanation about various processes of fine particles in porous media, including pore surface release, pore surface retention, pore throat release, and pore throat plugging. The most recent equations by Civan [14] include additional empirical parameters accounting for heterogeneities related to pore structure and pore surface properties.

Table 2. 4: Pore-surface release rate equations (U_{cr} is critical superficial velocity, υ_{cr} is critical interstitial velocity, $\Delta\sigma_a$ is the concentration of released particles, σ_{ao} is initial attached fines concentration, σ_{cr} is critical retention concentration, T is temperature, γ is salinity, γ_{cr} is critical salinity, λ_p and λ_d are rate coefficients and λ_b , η , $m1$ and $m2$ are empirical constants)

Reference	**Kinetic Equation**
Khilar and Fogler,1983 [8]	$\frac{\partial \sigma_a}{\partial t} = -\lambda_d \sigma_a$
Gruesbeck and Collins,1982 [25]	$\frac{\partial \sigma_a}{\partial t} = -\lambda_d\, \sigma_a (U - U_{cr})$
Civan and Nguyen, 2005 [90]	$\frac{\partial \sigma_a}{\partial t} = -\lambda_d\, (\eta\, \sigma_a)\, \varphi^{2/3} (\tau - \tau_{cr})$
Wang and Civan, 2005 [91]	$\frac{\partial \sigma_a}{\partial t} = -\lambda_d\, \sigma_a (\upsilon - \upsilon_{cr})$
Bedrikovetsky, 2010 [9]	$\Delta\sigma_a = \sigma_{ao} - \sigma_{cr}\ ,\ \sigma_{cr} = \sigma_{cr}\, (\upsilon\ \gamma\ pH\ T)$
Kord et al., 2014 [92]	$\frac{\partial \sigma_a}{\partial t} = -\lambda_d\, \sigma_a (\upsilon - \upsilon_{cr})$
Civan, 2016 [14]	$\frac{\partial \sigma_a}{\partial t} = -\lambda_d\, (\eta\, \sigma_a)^{m1}\, \varphi^{m2} (\upsilon - \upsilon_{cr})\, (\gamma_{cr} - \gamma)$
Coranado et al., 2017 [93]	$\frac{\partial \sigma_a}{\partial t} = -\lambda_d\, U (\sigma_a - \sigma_{cr})$

Table 2. 5: Pore-throat plugging /bridging rate equations.

References	Kinetic Equation
Herzig et al.,1970 [7]	$\frac{\partial \sigma_p}{\partial t} = \lambda_p \, U C_m$
Gruesbeck and Collins,1982 [25]	$\frac{\partial \sigma_p}{\partial t} = \left(\lambda_p + \lambda_b \; \sigma_p\right) U \; C_m$
Civan and Nguyen, 2005 [90]	$\frac{\partial \sigma_p}{\partial t} = \left(\lambda_p \; + \lambda_b \; \varphi\right) U \; C_m$
Wang and Civan, 2005 [91]	$\frac{\partial \sigma_p}{\partial t} = \lambda_p \left(1 + \lambda_b \; \sigma_p\right) C_m \; \varphi \; U$
Lohne et al., 2010 [94]	$\frac{\partial \sigma_p}{\partial t} = \lambda_p \, \upsilon \; C_m$
Kord et al., 2014 [92]	$\frac{\partial \sigma_p}{\partial t} = \lambda_p \left(1 + \lambda_b \; \sigma_p\right) C_m \; \varphi \; (\upsilon - \; \upsilon_{cr})$
Civan, 2016 [14]	$\frac{\partial \sigma_p}{\partial t} = \lambda_p \left(1 + \lambda_b \; \sigma_p\right) U \; {C_m}^{m1} \varphi^{m2}$
Coranado et al., 2017 [93]	$\frac{\partial \sigma_p}{\partial t} = \lambda_p \, U C_m (1 - \sigma_a / \sigma_{cr} \,)$

According to the kinetics equations, the release rate is proportional to driving forces as the difference between the current and critical velocity and salinity values. The plugging rate is also proportional to convective flux ($U \; C_m$) of mobile fine particles.

It is stated that the kinetic equations for the release mechanism cannot support the experimental results of abrupt variation in permeability caused by abrupt changes in flow rate or salinity [9, 11, 95]. They result in the prediction of permeability behavior with delay as time goes to infinity. Bedrikovetsky et al. [9] substituted the classical release rate equations with an alternative model that supports the abrupt permeability responses observed in coreflood tests. The authors introduced a phenomenological function known as critical retention (attached) concentration depending on velocity, salinity, pH, and temperature. The fine particles are detached until the attached concentration reaches a critical retention concentration upon changes to flow conditions. An instantaneous release process is assumed for hydrodynamic release, but a delay time factor is considered for the chemical effect [11, 34]. The critical retention concentration was derived based on the torque balance of attaching (electrical and gravitational) and detaching (lifting and drag) forces exerted on a fine particle attached to pore surfaces. Some simplified theoretical expressions of this function have limitations and complexities in calculating input parameters [11]. Nevertheless, in modeling applications, the difference of critical retention concentrations in two different flow conditions (current and previous velocity and salinity conditions), known as the released particles' concentration, is determined by matching the experimental data [11, 34, 96].

In recent modeling studies, a drift delay factor (α) as the ratio of mobile fine particles velocity and fluid flow velocity is incorporated into the fine particles transport and plugging equations [9, 11, 34, 87, 96, 97]. This factor is attributed to fast and slow velocities of moving particles in the bulk flow and close to pore surfaces, respectively. Long-term stabilization of permeability after many pore volume injections in coreflood tests justifies this parameter [11, 96].

2.5.2.1 *Porosity and permeability variation*

The instantaneous porosity of the porous media can be given based on the volumetric concentration of released and plugging fine particles:

$$\varphi = \varphi_o + (\sigma_{ao} - \sigma_a) - \sigma_p \tag{10}$$

where, φ_o is the initial porosity, σ_p is plugging fines concentration and the term $(\sigma_{ao} - \sigma_a)$ is released fines concentration.

Several empirical expressions have been proposed for the permeability variations relative to initial permeability based on porosity and concentration of plugging particles [7, 10]. The frequently used equation in recent fines migration studies is based on 1) the assumption of small release and plugging fines concentrations, and 2) considering the zero and first terms of a Taylor series expansion of permeability variation, as follows [9, 11, 34, 93]:

$$\frac{K(\sigma_a \ \sigma_p)}{K_o} = \frac{1}{1 + \beta_a(\sigma_a - \sigma_{ao}) + \beta_p \sigma_p} \tag{11}$$

where K is the instantaneous permeability, K_o is the initial permeability, and β is the formation damage coefficient. Parameters β_a and β_p are formation damage coefficients because of attachment and plugging of fine particles at pore surfaces and pore throats. These parameters depend on particle and pore size distribution, and then they are a function of released and retained concentrations. However, they can be assumed constant for small release and retention concentrations [34]. For the case that the effect of release term $(\sigma_a - \sigma_{ao})$ is significant, permeability increases. In an experimental-based modeling approach, the measured pressure drops and produced fines concentration data can be matched with simulation data by solving corresponding reverse problems to determine the empirical parameters.

2.6 Proposed Workflow for Sand Control Design in Unconsolidated Sands

Experimental studies under representative conditions are essential to select the optimum design configurations before running the screen in the well. The sand retention test (SRT) equipment with various features, sizes, and testing procedures is used to evaluate sand control and flow performance of a sand control screen [64, 68].

Most of the previous SRT experiments partially investigated the fines migration inside the porous media. The screen evaluations are performed based on sand production and retained permeability measurements in a testing that allows for quick flow stabilization. Performing a series of time-lapse experiments and visual inspection of the slots indicate that sand grains alone do not plug the slots. The infill and tight packing of fine particles around the sand grains adjacent to the slots have been found to induce low retained permeabilities [21]. More recently, an SRT setup **(Figure 2.10)** has been frequently used to assess various screen configurations considering measurements of the produced and retained fine particles. The tests, however, neglect the interaction of fines migration with other formation damage mechanisms, including chemical (organic and inorganic scaling, clay swelling) and thermal damages (mineral transformation, dissolution), and also liner fouling, are not considered in a sand retention test.

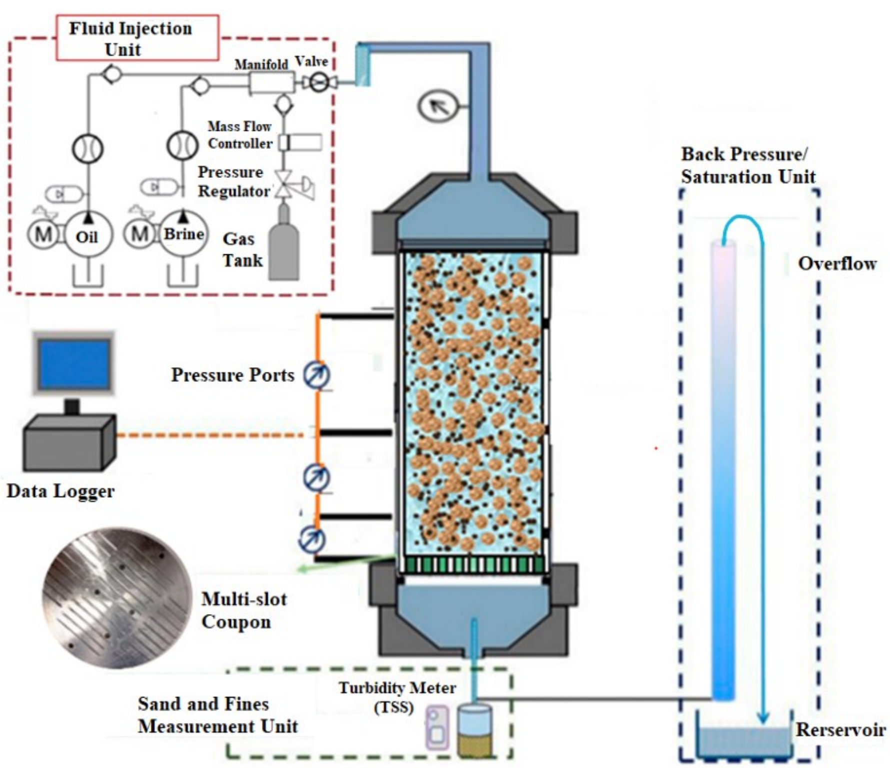


Figure 2. 10: Linear flow Large-Scale Sand Retention Test (SRT) setup [35, 56, 49, 53, 57, 58].

The setup provides linear single-phase and multi-phase flow tests. The sand sample is packed on a 6-inch screen coupon up to 17 inches in length. A small axial load is just applied to prevent the fluidization of the sample. This packing procedure emulates the case of the rapid collapse of formation sand over the screen (zero effective stress) in SAGD wells during the early life of the well before stress evolution [64, 68]. Multi-slot coupons of slotted liners can be used to assess the effect of slot density instead of previous single-slot tests [64]. Although employing such a large-scale setup allows long-term flow conditions and also minimizes the boundary effects, it demands a large amount of reservoir formation sand and fines that may not be available or be costly. This issue is typically circumvented using commercial sands with a PSD and shape factor properties that match natural oil sands [35, 64]. However, commercial sands' surface properties affect the fines migration process and may not represent natural oil sands.

The Fail/Pass criteria in the literature to select an optimum screen design are generally based on acceptable levels of sand production (less than 0.12 lb/ft^2 or 1% of slotted liner volume) and retained permeability (higher than 70%) [56, 64]. In some works, the optimum slot width inferred from single-slot SRT is presented as a function of specific points on the PSD of the sample [71]. A recent presentation is based on a color code similar to a traffic light known as Traffic Light System (TLS). The TLS labeled with D values (e.g., D90 is the mesh size that 90% of particles have a diameter greater than this value) of the PSD allows to specify unacceptable (red), marginal (yellow), and acceptable (green) slot widths for different slot density and flow conditions [35]. In the current uses of TLS, lower and upper bounds of 0.12 lb/ft^2 and 0.15 lb/ft^2 for sand production and 50% and 70% for retained permeability are considered [35,56,57,71]. **Figure 2.11** demonstrates a typical TLS for the performance of different sizes of slotted liner coupons.

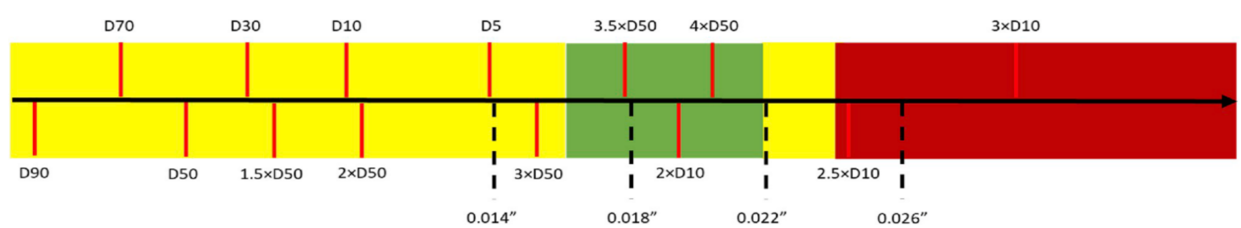
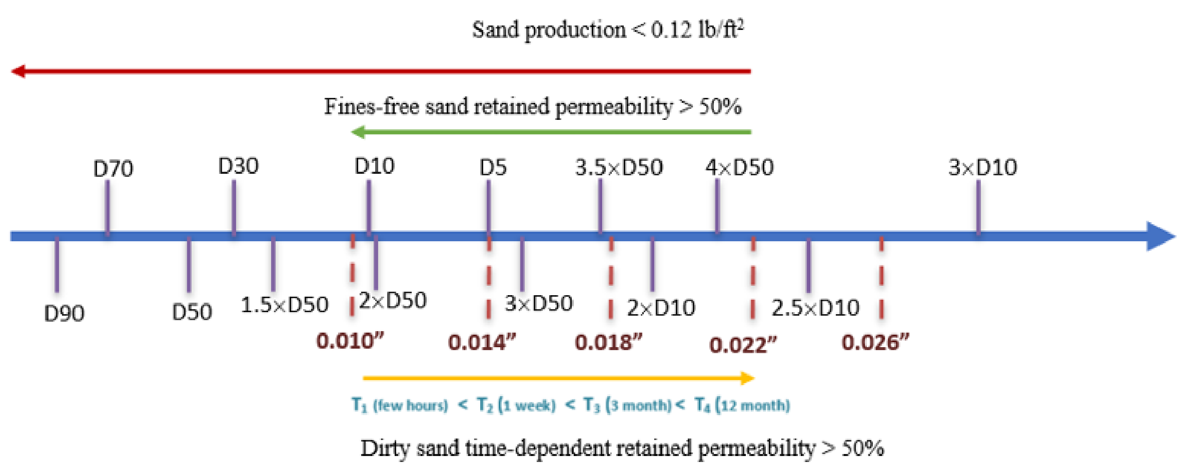


Figure 2. 11: Traffic light system for slotted liners with different aperture sizes (dashed lines), slot density 30, and flow rate <0.72 bbl/day/ft [71]

The fines migration process in an SRT setup with a screen coupon can be simulated using a coupled 3D numerical model. The numerical model can evaluate the effect of different combinations of influencing factors under the representative rock and fluid properties. Conducting such an evaluation in a large-scale SRT setup is expensive and time-consuming. The modeling's critical steps would be calibrating (to determine empirical parameters) and validating the model based on the experimental results. For this reason, appropriate physics governing the fines migration process should be incorporated. Because of the narrow screen apertures, the model would include a computationally extensive mesh, which requires an efficient calibration procedure. However, theoretically, the empirical model parameters are porous media characteristics independent of the screen specifications. Therefore, they can be determined by matching experimental and simulation results for a specific sand pack with simple geometry without the screen coupon.

In a representative fines migration experiment, the short-term retained permeabilities may increase or decrease depending on the concentration of migrating and retained fine particles in the completion zone. If migrating fine particles are accumulated progressively in the completion zone, the retained permeability would decrease. In contrast, the retained permeability increases if fines migration is insignificant or the fine particles are discharged near the screen [13].

As depicted in **Figure 2.12**, the screen design for dirty sands (sands with high fines content) based on short-term evaluations can be misleading.



Red: Acceptable slot sizes with respect to sand production stabilized in the short term for both fines-free and dirty sands.

Green: Acceptable slot sizes with respect to sand production and retained permeability stabilized in the short term for fines-free sands. The retained permeability is affected by resorting and bridging of sand grains over the SCD. Smaller size is preferred for better sand control performance.

Yellow: Acceptable slot sizes with respect to sand production and retained permeability for dirty sands. The retained permeability is affected by combined effects of sand grains resorting/bridging and fines migration process. This is not a short term process (typically several days in lab and several months in field). Larger size is pereferd for long-term performance.

Figure 2. 12: Demonstration of design constraints for fine-free and dirty sands.

For clean sands, typically, the smallest aperture size which passes the retained permeability constraint would be chosen (e.g., 0.014" in **Figure 2.12**) [35, 71]. However, the smallest aperture size would be plugged drastically after a while for dirty sands, owing to fines migration. It is reasonable that wider aperture sizes are chosen, which would plug in a much longer time (e.g., 0.022" in **Figure 2.12**). Therefore, based on short-term retained permeability evaluation, an aperture size may be selected that is more narrow for better sand retention performance but not wide enough to discharge fine particles in the long term.

To account for the screen's long-term flow performance in dirty sands, a workflow **(Figure 2.13)** is proposed based on the numerical simulation of the fines migration process. In the first stage, simulation is performed at the laboratory scale to match the experimental results and obtain the essential modeling parameters. Performing a laboratory-based numerical simulation in this scale allows incorporating the SCD geometry. The contribution of SCD to the retained permeability evolution with time under the fines migration process can be evaluated as a skin factor by conducting separate simulations with and without SCD. The second stage includes modeling the fines migration process on a well scale. The skin factor obtained from the previous stage will be applied here as SCD geometry will not usually be considered in well-scale modeling. In case of available field data of flow rate or pressure drop variations under the fines migration process, the well scale model can also be calibrated to obtain more accurate model parameters. Otherwise, the model parameters obtained from the laboratory scale can be applied. The near-wellbore modeling can be performed by implementing an efficient approach for coupled near-well and reservoir modeling [98]. In the last stage, the well model can be used to predict the retained permeability under the fines migration process and design SCD for the long-term life of the well based on the criteria earlier explained.

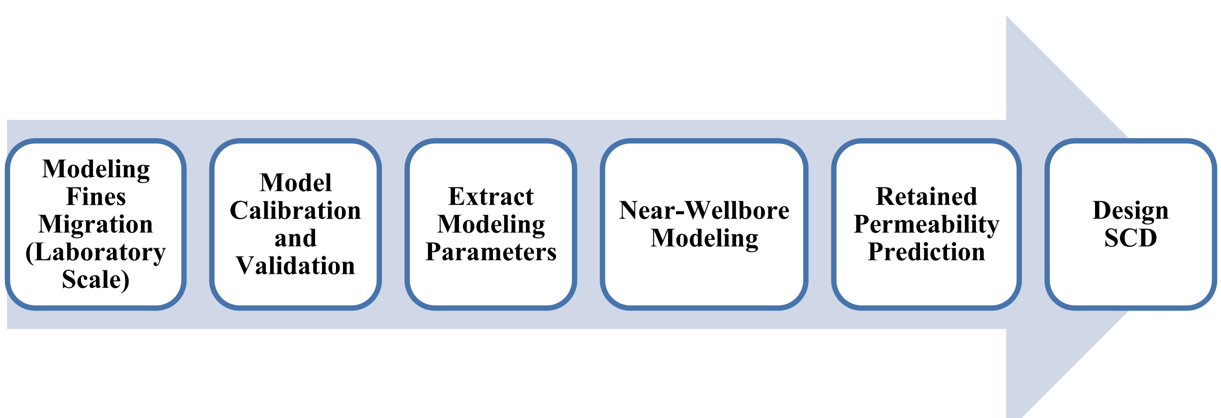


Figure 2. 13: Proposed workflow for SCD design accounting for transient behavior of the fines migration process.

2.7 Summary

This paper reviews the fines migration process in porous media with particular attention to the SAGD near-wellbore region. Field observations and coreflooding experiments confirm the well productivity impairment and screen plugging in SAGD wells due to the fines migration process. Theoretical and experimental studies demonstrate the significance of particle and pore size distribution, flow velocity, salinity, pH, temperature, fines content, fines wettability, effective stress, and well completion on the fines migration process.

Macroscopic models have been frequently used in lab-scale studies to predict the macroscopic distribution of fine particles within the porous medium and estimate the permeability variation under the fines migration process. These models include empirical kinetic equations for different mechanisms of release and retention of fine particles within porous media. Some model parameters need to be determined by matching the experimental data. The past macroscopic models were mainly developed for consolidated sands and did not consider the interaction of the porous medium with the sand control screen.

The sand control screen's effect on the retention of fine particles in the near-wellbore sand and the production of migrating fine particles have not been adequately explored through a representative test procedure. The current sand retention tests for evaluating the sand control performance account for short-term pressure stabilization. However, they are not designed to incorporate the long-term interaction between the fines migration and other plugging mechanisms such as organic and inorganic scaling.

This paper also proposes an alternative workflow to investigate the long-term flow performance of the sand control device in sands containing fine particles. To implement the proposed workflow, numerical modeling of the fines migration process at the laboratory and wellbore scales is necessary. The mathematical model can also help investigate the effect of several combinations of contributing factors, which is expensive and time-consuming through SRT experiments.

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Chapter 3: Novel Laboratory Methodology for Fines Migration Testing for SAGD Wells

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3.1 Preface

The sand retention and the retained permeability or flow performance of sand control screens in unconsolidated formations are usually evaluated through the pre-packed sand retention testing (SRT) procedures. These procedures attempt to address a complex process of fines migration which influences the flow performance of screens in formations with relatively high fines content. Plugging of sand control screens and flow impairment of SAGD wells in unconsolidated Alberta's oil sands is a common problem in which the role of fines migration is prominent. Previous SRT studies for the SAGD wells did not purposefully explore the fines migration process. In this study, a set of pre-packed SRT experiments with comprehensive long-term testing procedures were conducted to simulate the fines migration process and assess the flow performance behavior of a sand screen under SAGD well conditions.

The experiment results indicate a non-monotonic behavior of permeability with an initial decrease followed by an increasing trend for the near screen interval of the sand pack. It is observed that the effect of releasing fine particles from or near the pore throats on permeability is dominant compared with the retention of fine particles over the thin pore throats at the first stages of the experiments. Because of testing limitations concerning initial attachment of fine particles at pore surfaces, pore size distribution, and the amount of mobile fine particles as a function of time, most results were inconsistent with decreasing trend behavior of permeability in the field and actual core flooding observations. However, a decreasing behavior was observed by conducting a new test procedure replicating a representative worst-case flow condition in the field. As the main conclusion, the previous SRT test procedures and the design criterion should be revised to enhance the flow performance assessment of sand control screens for formations susceptible to the fines migration process.

3.2 Introduction

Steam-assisted gravity drainage (SAGD) wells recover bitumen from unconsolidated oil sands prone to sand production, necessitating sand control screens to prevent sand from getting into the wellbore. The current design criteria for evaluating different sand screen designs are based upon a trade-off between sand retention performance and flow performance of the sand screens with given formation sand. Assessment of these performances is usually achieved experimentally using a sand retention testing (SRT) apparatus in which either a representative sand sample packed over the screen (Pre-packed SRT) or a low concentration of sand slurry flows toward the screen (Slurry SRT) [1]. The latter simulates the case where there is an annular gap between formation and screen, and sand particles carry with fluid flow. However, it is reasonable to assume a rapid collapse and redistribution of unconsolidated sand over the screen in SAGD wells. Therefore, pre-packed SRT would give more representative results. In these experiments, the amount of produced sand and the near-screen permeability (retained permeability) are measured to evaluate the sand retention and the flow performance.

It should be borne in mind that the screen should be selected so that it is suitable for controlling the amount of sand production and effectively dealing with the phenomenon of fine particle production (i.e., in case the reservoir is prone to fines production). Fines are usually considered particles smaller than 44 μm and include clay minerals such as chlorite, smectite, kaolinite, illite, and non-clay minerals such as quartz, silica, feldspar, mica, calcium, and dolomite. These particles are not bonded to the sand grains and can migrate under certain flow conditions [2, 3]. The net repulsive force resulting from hydrodynamic (drag and lift) and physicochemical (electrical double layer) interactions is responsible for releasing fine particles [4, 5].

There are strong pieces of evidence from laboratory and field observations indicating that migrating fine particles could plug thin pore throats within the porous medium and damage the near-well permeability [5, 6]. Fine particles would also easily migrate or redeposit in low-velocity areas, altering the screen permeability [7, 8]. Therefore, the screen should be designed to minimize screen and pore plugging by its optimum geometric specifications to discharge the migrated fine particles near the screen while preventing sand production.

Field-scale sand production is a relatively fast process, and it can be considered a short-term phenomenon in terms of time scale. Moreover, the time taken for routine SRT experiments is well in line with field reality, and it can be said that laboratory conditions replicate field conditions. However, it should be noted that fine particle production is relatively slow and can be considered a long-term phenomenon in terms of time scale. The amount of time considered for routine experiments is not well suited to field reality, and it can be said that laboratory conditions do not replicate field conditions.

Many researchers studied the performance of different sand screens such as slotted liner (SL), wire-wrapped screen (WWS), and punched screen (PS) for the SAGD wells using a pre-packed SRT apparatus where flow is linear toward the screen on the bottom of the sand pack [9-16]. The tests were carried out on commercial sands with particle size distribution (PSD) representative of four PSD classes of McMurray formation with a fines content of 1%, 5%, 7%, and 14.5%. Single-phase (brine) and multi-phase (brine, oil, and nitrogen) flow tests under SAGD flow conditions concerning salinity, pH, and typical flow rates in the range of 1000-4500 bbl/day were conducted in these works. Some tests were conducted to assess the impacts of salinity, pH, and stress on the fines migration. However, the tests have some limitations regarding the actual high reservoir pressures and temperatures, actual reservoir sands and fluids, and the radial geometry of the flow. More details about these tests are given in a critical review paper by the authors [17].

Through the above works, the laboratory procedure for choosing a proper sand screen device (SCD) to control the produced sand is well established, and corresponding design criteria are also well defined. For instance, a sand production level of less than 1% of equivalent sand screen volume and the retained permeability higher than 70% of the initial sand pack permeability have been considered acceptable sand retention and flow performance rules in these studies, respectively. However, these works have not thoroughly investigated the effect of the fines migration process. The test duration (up to three pore volume injections) is not selected correctly. Therefore, the results are misleading, and the selected screen is severely overdesigned (i.e., systematically choosing a screen with a narrow aperture). In fact, the measured retained permeability would only account for (1) the flow resistance of the screen after the quick stabilization of the sand layer over the screen and (2) the geometric flow convergence effect owing to changes in the streamlines and velocities near the screen but neglect near-wellbore permeability alterations du to fines retention.

The present study uses a normalized time-dependent criterion to design fines migration testing that represents the field time scale. The testing design accelerates the fines migration and plugging in accordance with dimensional analysis. The primary objective is to replicate the fines migration process in sand retention testing, considering the representative oil sand and flow conditions in SAGD wells to assess the flow performance of the sand screen. The rest of this paper is structured as follows. Section 2 provides a short introduction to the theoretical background of fines migration. A detailed description of the experimental setup and the methodology for performing fines migration tests is provided in Section 3. The experimental results and interpretation of the results are presented in Section 4. A discussion about the proposed reliable procedure for the fines migration testing in SRT experiments for the SAGD wells is given in Section 5.

3.3 Fines Migration Theory

A brief description of the physics and mechanisms of the release and capture of fine particles within the porous medium are presented here. The authors provide more details about the fines migration process around the SAGD wells in a recent review paper [17]. Despite several interchangeable terminologies for the fines migration mechanisms in different contexts, generally, the process would include four primary mechanisms as shown in **Figure 3.1**: Pore surface release (detachment), pore surface capture (attachment), pore throat release (dislodgement), and pore throat capture (straining, bridging and plugging). Detachment of fine particles from the pore surface occurs when repulsive forces dominate. The repulsive lift and drag forces depend on flow velocity and direction, while the repulsive electrical double layer (EDL) force depends on ionic strength (salinity, pH) and temperature [6, 18]. Also, all forces depend on particle size.

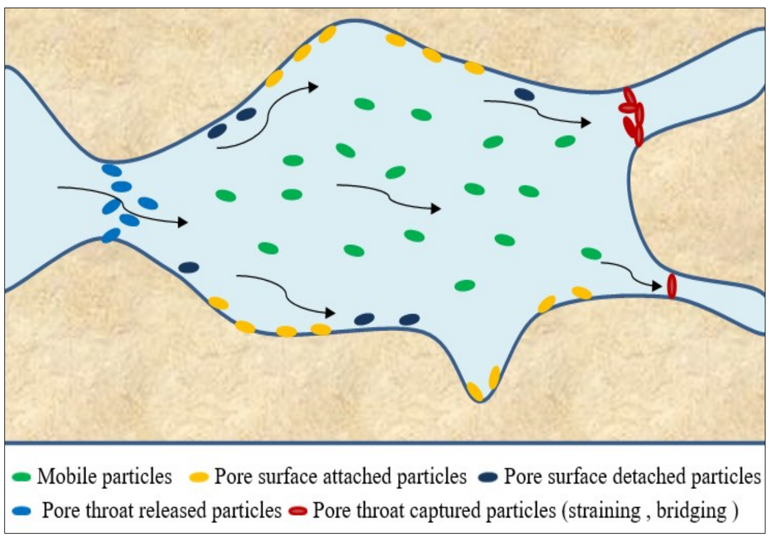

Figure 3. 1: Schematic of fine particles release, migrate and capture mechanisms in a pore space [17].

The fluid flow under high velocity, low salinity, high pH, and high temperature creates conditions favoring the detachment mechanism. Fines release intensifies under high flow velocity and low salinity conditions [5,19-23].

The pore throat capture mechanisms are mechanical and hydrodynamic related mechanisms that depend on the pore size distribution of the porous medium and the convective flux of mobile fines [19, 24, 25]. Pore throats with sizes less than fine particles are plugged mechanically and eliminated from the flow paths. On the other hand, hydrodynamic effects could establish stable bridges on pore throats followed by fines accumulation when multiple particles simultaneously approach the pore throats [2, 26, 27]. Furthermore, inertial forces could deviate the particles from the streamlines in high velocity and spatially varying velocity regions associated with radial flow converging toward the wellbore. Subsequently, particles impact the pore or pore throat walls and are retarded, enhancing the accumulation of fine particles [28].

Pore throat particle release occurs when the axial force caused by the pressure gradient reaches a critical value that breaks some of the bridges. Pressure surges and flow reversals could cause higher pressure gradients to break unstable bridges [2, 25]. In the context of the fines migration process, the pore surface deposition mechanism referred to as reattachment can occur when fine particles release from high-velocity areas near or at pore throats and deposit at low-velocity areas or dead-end zones [7, 29]. Generally, in the fines migration process, it is assumed that pore surface release and pore surface attachment mechanisms do not significantly change the permeability of the porous medium, and most pressure drop occurs at pore throats [5, 7, 30].

3.4 Experimental Study

This section presents a detailed description of the experimental set-up and the methodology for performing fines migration through a sand sample packed over a circular sand screen coupon emulating near-wellbore conditions in SAGD wells.

3.4.1 Sand retention testing (SRT) set-up

The laboratory set-up recognized as sand retention testing (SRT) equipment consists of several components, including a cylindrical cell with an inner diameter of 6 inches and length of 18.5 inches (recognized as large-scale dimensions), injection system, top platen with injection ports, base plate accommodating sand screen coupon, axial loading system, pressure transducers, backpressure column, sand and fine particles measuring component, turbidimeter, and data acquisition system. Fine particles are flowed out of the sand pack through a backpressure column. **Figure 3.2** demonstrates a schematic diagram of different components of the setup.

Fluids are injected from the top at a constant flow rate using triple-head diaphragm pumps. Each pump head would deliver a flow rate in the range of 660-7200 cc/hr. The pulsations generated by the pumping mechanism are damped using two pressure dampers mounted in series in the injection line. A graduated cylinder is used to measure the volume of produced fluid and monitor the flow rate during the flow test. The sand screen coupon (6 inches in diameter) sits at the bottom of the cell, on which the sand sample is packed. A porous disk is placed at the top of the sand pack to facilitate the uniform distribution of the flow. Axial stress up to 200 psi can be applied to prevent sand fluidization and flow channeling and minimize effective stress variations for high flow rates, especially when studying the fines migration process.

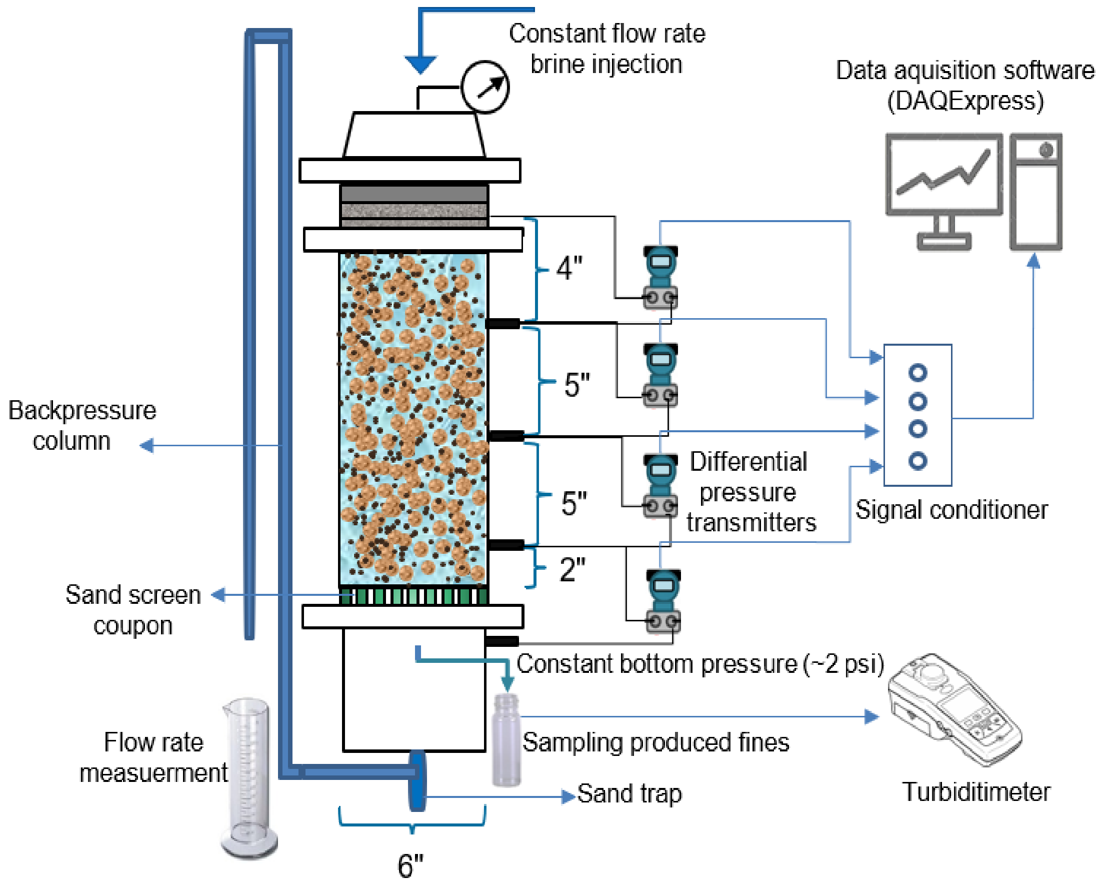

Figure 3. 2: Schematic of different components of the sand retention testing set-up.

Four differential pressure transmitters with ± 0.2% accuracy at full scale (15 psi), equivalent to the uncertainty of ± 0.03 psi, record the pressure drop over the sand screen and sand pack at different intervals. Measuring instant pressure drop variations at different intervals allows for tracking the fines migration process within the sand pack. The pressure drop over the sand screen and within the first 2 inches of the sand pack is considered the near-screen pressure drop to evaluate the flow performance of the sand screen.

Samples of the effluent fluid are taken at the outlet at specific time intervals. A calibrated turbidimeter with a maximum range of 1000 NTU equivalent to 3000 ppm determines the concentration of fine particles in the samples. The produced sand is collected through an elbow-shaped small pipe at the output as the sand trap. However, for the fines migration study, the size of the sand screen is usually selected for its optimum sand retention performance. Therefore, negligible sand production is expected. A backpressure column provides a constant hydrostatic pressure (up to 2 psi) at the outlet during initial saturation and flow tests.

3.4.2 Sand pack preparation

Following previous studies [9, 11, 12, 14, 16], commercial sands, silts, and clays were mixed to prepare sand pack samples with particle size distribution (PSD) representing oil sands of McMurray formation in Alberta, Canada. This formation is categorized into four major PSD classes [31]. In this study, a very fine sand class as DC-I with 14.5% fines content and a medium sand class as DC-III with 5.5% fines content were reproduced for the fines migration study. **Figure 3.3** shows reasonable agreements between the PSD of synthetic sand packs and the formation sands. Fig. 3 also shows the PSD of the fine-grained minerals of the sand packs. As can be seen, more than 80% of particles are less than 44 μm.

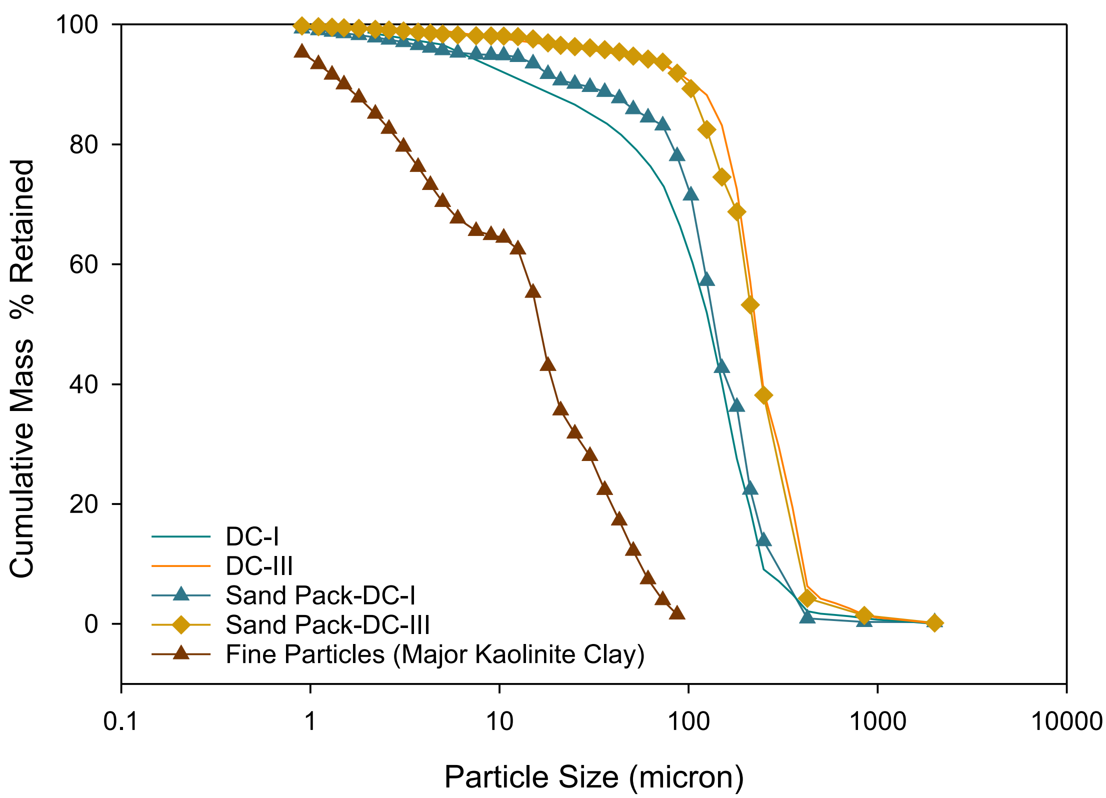

Figure 3. 3: Particle size distribution of formation sands, sand packs, and fine particles.

3.4.3 Sand control screen

A 6-inch circular coupon of a 7-inch-diameter slotted liner screen, as a popular SAGD sand screen, was used [32]. Slot aperture of 0.01 inches and slot density of SPC 42 were considered. According to previous studies [9, 12], such a design would result in insignificant sand production due to low open flow area (<1%) and small aperture. The slot density here is referred to the number of slots per column (SPC) of slots on the screen. It also corresponds to one-fourth of the number of slots per foot of the screen. Furthermore, as shown in **Figure 3.4**, a wire mesh screen with a 0.0095 in. aperture size (nearly the same as the slotted liner slot width) and an open flow area close to the sand pack's porosity (i.e., 35%) was used for flow performance comparison.

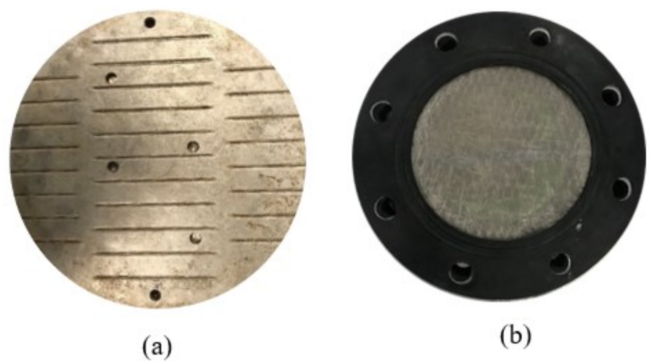

Figure 3. 4: (a) sand screen coupon (type: slotted liner; slot width: 0.01 inches; slot density: 42 SPC; opening: 1.3%) (b) wire mesh screen 60 (aperture size: 0.0095 inches; opening: 37%).

3.4.4 Fluid flow properties

For SAGD wells, produced brine mainly contains sodium chloride salt with salinity concentrations in the range of 400-3000 ppm and pH levels of 7.1-8.8 [33]. Low salinity values for the produced water compared with those for formation water, mainly in the range of 10,000-279,000 ppm for McMurray formation [34], are due to the mixing of steam condensate with formation water moving toward the production well. The produced water salinity is expected to decrease with time as more formation water is produced in the vicinity of the wellbore, reaching a value near the critical salt concentration that releases fine particles by chemical effect. In some cases, the fine particles near the wellbore can be exposed to the fresh steam condensate due to the steam chamber approaching the production well.

Typical production rates of the SAGD wells are between 1000 bbl/day to 4500 bbl/day [1]. These field values correspond to the lab injection flow rates of 300-1350 cc/hr per screen coupon area (0.20 ft^2) of a 7-inch-diameter slotted liner installed over an 800 m horizontal SAGD producer well. The testing procedure was designed to represent a worst-case scenario for the fines migration process in SAGD wells. Therefore, the sample was initially packed and saturated with 400 ppm

NaCl brine. Then, fluid flow was established with 400 ppm NaCl brine injection at flow rates of one to two orders of magnitude more than field values. In some flow stages, deionized water (DI) was used to release more fines under a chemical shock effect.

High flow rates account for nonuniform flow over the wellbore trajectory, high flow through open slots with severe screen plugging, and aggressive ramp-ups [9, 12, 17]. The chemical shock scenario could be justified for the SAGD thermal process where fines are released from the pore surfaces in direct contact with steam condensate. A more representative SAGD chemical shock scenario would be injecting 400 ppm brine into a sample already saturated with high salinity brine (e.g., 20000 ppm) as formation brine. It is thought that at the edges of the SAGD steam chamber, the condensate steam can pick up some salt minerals from the formation and, therefore, an elevated salinity near the producer well would be expected.

The near-wellbore temperature of the SAGD producers is in the range of 220 °C to 350 °C, depending on the reservoir depth [9]. Under these elevated temperatures, the net repulsive force to detach fine particles from pore surfaces is reinforced. However, due to experimental difficulties and high costs, current SRT experiments for the SAGD wells are limited to low pressure and temperature conditions.

3.4.5 Methodology for fines migration study

This section explains the testing procedure. Several stages of the tests consisted of sample compaction, sample saturation, brine injection, and postmortem analysis. The pressure, flow rate, and produced fines concentration data were acquired for further analysis.

The moist tamping method was used for sand pack compaction. Brine at 10.0 wt% was added to the sand sample and mixed for 20 minutes to obtain a homogenous sample. High salinity brine also keeps particles attached to the grains at initial conditions. Then, the sand sample was packed manually over the sand screen installed at the bottom of the SRT cell. Sand layers with a 1-inch thickness were subsequently packed till a target porosity of 35% was achieved. An under-compaction technique was applied to avoid higher compaction of bottom layers and obtain a consistent and uniform porosity over the length of the cell [35]. In addition, while compacting each layer, about 100 gr of the sand sample was taken to check the uniformity of the fines content in each layer by conducting a wet sieving procedure. The maximum length of the sand sample was

16 inches. However, shorter sand packs with 12 and 7 inches lengths were employed in some tests. The top part of the cell was filled with clean gravel to allow a uniform injected flow distribution.

After compaction, the sand pack was saturated slowly from the bottom using the backpressure water column and a low flow rate of about 100 cc/hr. The saturation stage started with removing air bubbles from the lines connected to the pressure transmitters to obtain accurate pressure measurements. The saturation stage lasted about 24 hours.

The initial permeability of the sand pack was determined at several intervals, as shown in **Figure 3.2**. The permeability assessment was carried out at low flow rates of 660-1560 cc/hr to avoid sample disturbance by fines migration. The initial permeability values also indicate sample consistency among different tests. Permeability calculations were done by applying Darcy's flow formula using pressure drop data and accounting for the gravity effects.

Fluid flow was established in the sample by injecting brine or deionized water from the sample top for the main flow tests. Pressure drop measurements within the sand pack were recorded for different intervals. The concentration of produced fine particles was also measured using a turbidimeter by taking effluent fluid samples every five minutes. Flow tests were continued until the stabilization of the pressure drops.

A stabilization criterion was considered based on the accuracy of the pressure transmitters. As a result, when the difference of consecutive pressure drops was ± 0.03 psi, the flow test was stopped or switched to another flow stage. Lastly, after completing the tests and disassembling the set-up, a full-length core was taken from the sand pack and cut into 1-inch slices. A sample of 100 grams of sand was taken from each slice, washed on a 44-micron sieve, and then oven-dried to obtain the mass of retained fine particles. As a result, the retention profile of the fine particles within the sand pack after the fines migration process could be determined.

3.5 Experimental Results and Analysis

As explained in the introduction, the primary objective of the experiments is to replicate the fines migration process in sand retention testing, considering the representative sand sample and flow conditions in SAGD wells to assess the flow performance of the sand screen. A basic test (*Test No.1*) is designed to consider the reservoir's actual conditions (e.g., flow rate, salinity, pH, slot width, and slot density) but with a much longer test time than standard SRT tests. This test determines whether the degree of permeability reduction in the short duration of standard SRT tests can be the basis for screen selection. Since the preliminary results contradicted the previous SRT observations, other experiments (*Test No.2-4*) were designed considering the effect of the area open to flow (AOF), fine particle distribution, mobile fines concentration, and fines content to ensure that the observations were not incidental. After this, Tests 5 and 6 were designed to modify the standard SRT procedure and achieve a method more consistent with the actual particle deposition conditions in the near well area. Twelve tests were conducted in total. Some tests were for repeatability checks and additional investigations. This section presents the main tests with the interpretation of the results. **Table 3.1** shows the specifications for the tests, which are presented here with their main features.

Table 3. 1: specifications of the conducted pre-packed SRTs.

Test No.	Screen Coupon	PSD	Fines content wt% (<44 µm)	Sample length (in)	Pore volume (cc)	Salinity (ppm)	Flow rate (cc/hr)	Pore volume injection (PVI)
1	Slotted liner	DC-I	14.5	16	2650	400	12000	75
2	Wire mesh	DC-I	14.5	16	2650	400	12000	42
3	Slotted liner	DC-I	6 (< 2 µm)	14	2450	400	12000	40
4	Slotted liner	DC-I	14.5	12	2250	DI	2000	3
5	Slotted liner	DC-III	5.5	7	1075	400	16000	85
						DI	7200	55
6	Slotted liner	DC-III	5.5	7	1075	DI	52000	75

3.5.1 *Test No. 1 (SL Coupon, DC-I sand, Hydrodynamic effect)*

This test was conducted under flow conditions reasonably representative of the near-wellbore of a SAGD producer exposed to a reservoir formation with high fines content. **Figure 3.5** shows the initial permeability of the sand pack in different intervals at the low flow rate of 700 cc/hr, corresponding to a relatively low superficial velocity of 4.57×10^{-5} m/s. Before conducting the main flow test, the sand pack had an initial permeability in the range of 270-290 mD.

The instant variations of pressure drops and permeability with fines migration at the flow rate of 12000 cc/hr (superficial velocity of 1.8×10^{-4} m/s) are shown in **Figure 3.6** and **Figure 3.7**. Due to a technical issue with the very top transmitter during the test, the pressure drop data for that interval were unreliable and not shown here. The permeability values at the beginning of this flow stage are much higher than those for the low flow rate stage in **Figure 3.5**. As this behavior was observed in all tests, an explanation is presented at the end of this section.

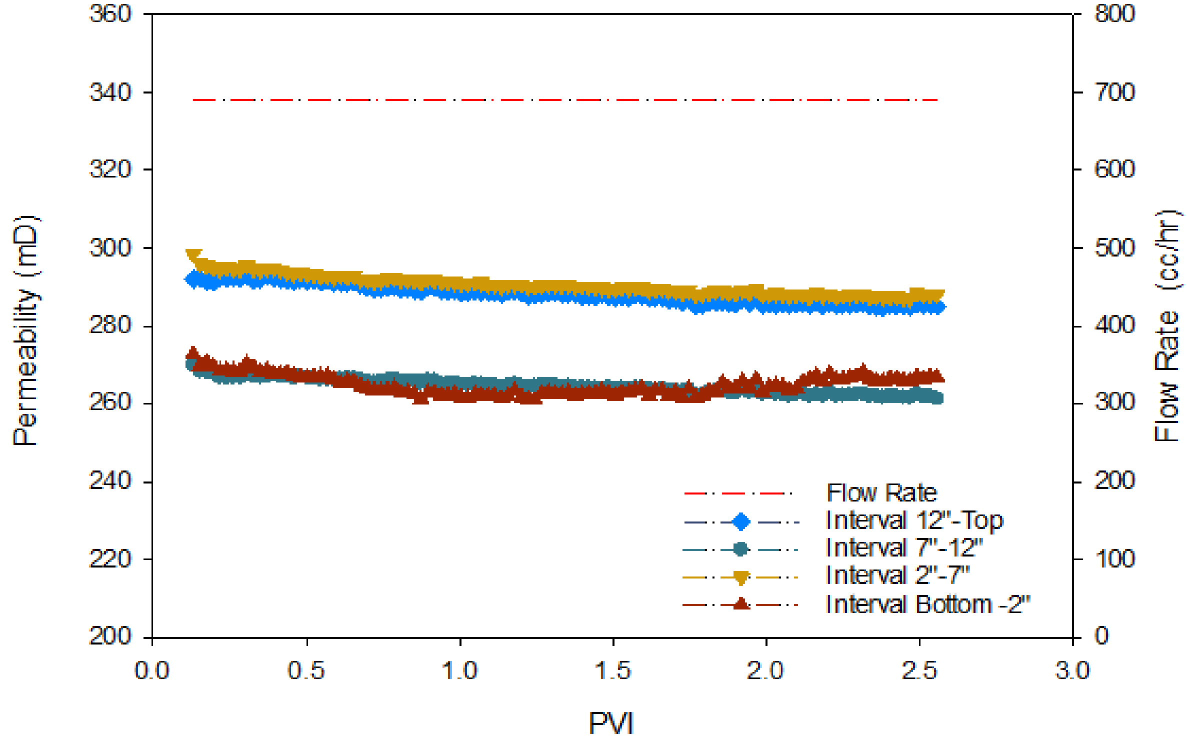

Figure 3. 5: The initial permeability of four intervals of the sand pack- Test No. 1.

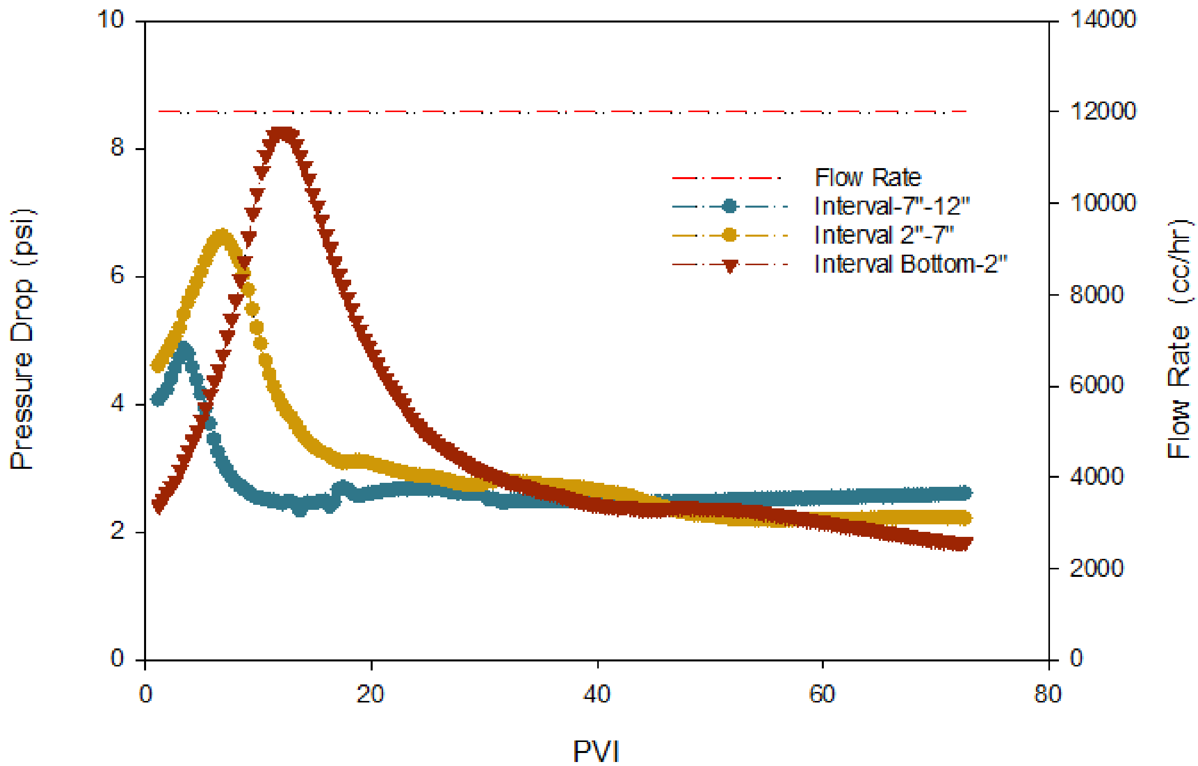

Figure 3. 6: Instant pressure drop variations at three intervals of the sand pack-Test No. 1.

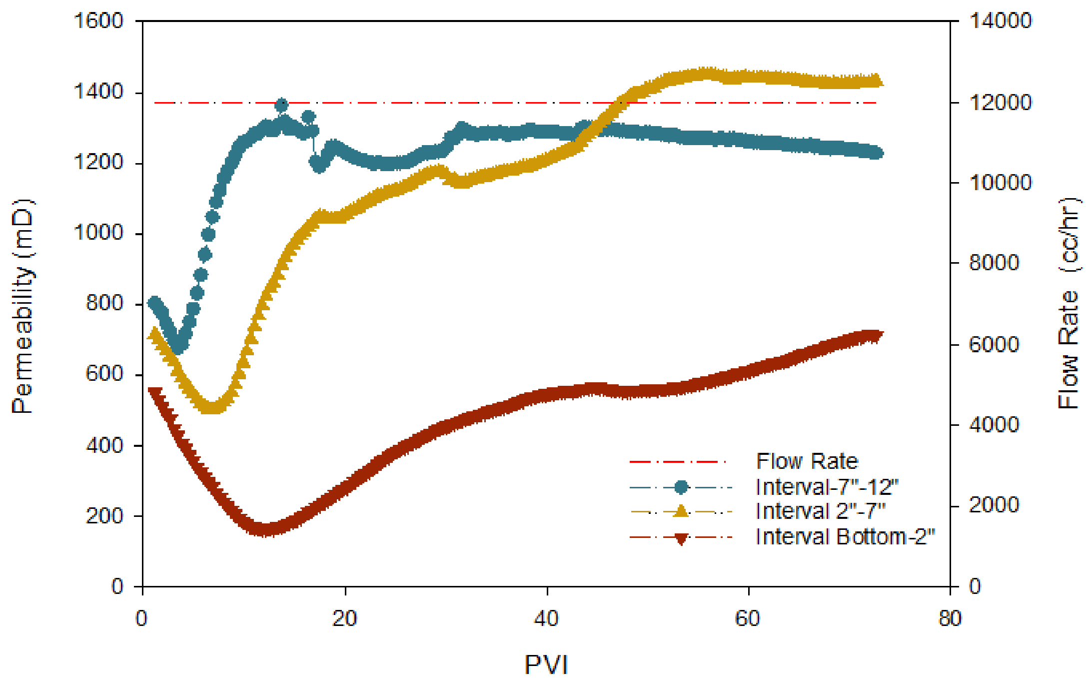

Figure 3. 7: Instant permeability variations at three intervals of the sand pack-Test No. 1.

As expected, the most pressure drop and permeability decline occurred at the bottom interval after 15 pore volume injection because of higher mobile fines concentration near the screen. However, all intervals experience a non-monotonic pressure drop and permeability behavior by increasing the number of pore volumes injected as a dimensionless time parameter. This behavior has also been observed for a wire-wrapped screen permeability through the tests performed on some well-sorted sands [36, 37].

The permeability variation indicates the release and capture of fine particles at the pore throats. The capture mechanism is dominant at the initial times. Later, the permeability improves by sweeping and migrating fine particles within the sand pack and producing through the screen. Under hydrodynamic effect, fine particles are mainly released near the pore throats where shear force and flow velocities are high or from the pore throats by high normal pressure gradients. Theoretically, most pressure drops occur at pore throats. Indeed, they are essentially responsible for increasing or decreasing the permeability of the porous medium. Fine particles would also be loosely placed at pore throats between large grains in a synthetic sand pack, reducing the intergranular porosity. These fine particles could be easily removed under sufficient hydrodynamic forces (critical flow velocity) and increase permeability significantly. However, fine particles are usually attached to the pore surfaces around a film layer of water in a natural oil sand sample [38].

The initial decrease in permeability in the test could be attributed to several retention mechanisms. They would include straining large particles at thin pore throats, clogging pore throats under direct interception (decreasing effective flow area), and plugging pore throats by high concentrations of small fine particles under a retardation and accumulation mechanism. The latter is significant near the screen due to the high concentration of mobile fines and low areal porosity at the sand pack and screen interface. The straining and plugging mechanisms eliminate some flow paths as pluggable pathways and divert the flow to the larger pore throats.

Higher flow volume passing through non-pluggable pathways causes the release of more fine particles from the pore throat surfaces, increasing the permeability. Therefore, different monotonic and non-monotonic behaviors of permeability depend on the concentration of the mobile fines, and particle and pore size distribution might be observed. In **Figure 3.7**, it is observed that the effect of release is dominant in high pore volume injections for the middle and top intervals leading to higher permeabilities than initial values. For the bottom interval, the permeability is recovered to a level slightly higher than the initial value for the bottom interval as more pore throats have been plugged in this interval. It is important to note that this non-monotonic behavior is not seen in standard SRT tests because the duration of the tests is short. As a result, only a decrease in permeability is reported. However, if enough time is given to the test, this permeability will increase again, and as a result, the selected screen is very pessimistic.

The graph of produced fines concentration in **Figure 3.8** shows a peak at the same pore volume injection for the permeability graph. At the initial times, due to high mobile fines concentration in the system, more particles reach the bottom and produce out through the screen. The cumulative amount of produced fine particles is significantly low in all tests under the hydrodynamic effect, indicating that a small mass of fine particles is mainly released from pore throats and captured in thin pore throats. The cumulative amount of produced fines is only 0.8 wt% of the initial fines content for this test. The retention profile of fine particles within the sand pack from the one-inch top (T) to the one-inch bottom (B) is shown in **Figure 3.9**. Although the measurements are a macroscopic measurement of the retained fine particles on pore throats, we can see an overall increasing trend of fines retention toward the bottom, compared with the mean initial fines content.

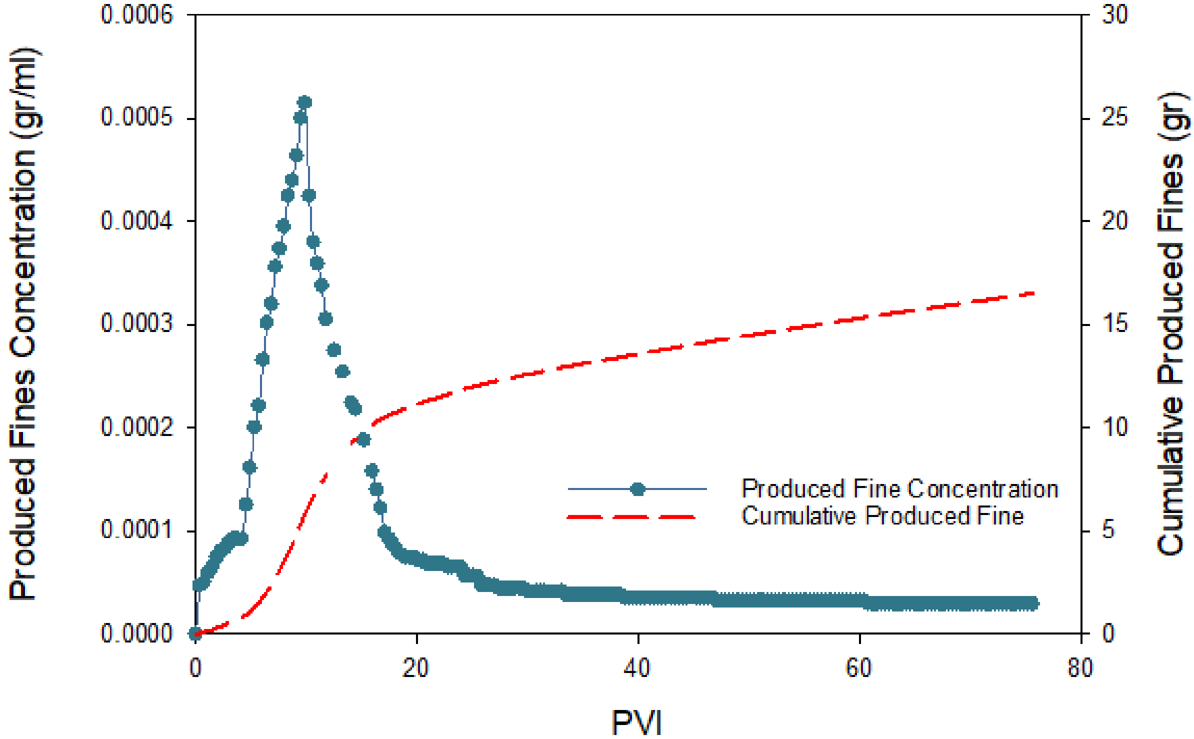

Figure 3. 8: Produced fines concentration versus injected pore volume -Test No. 1.

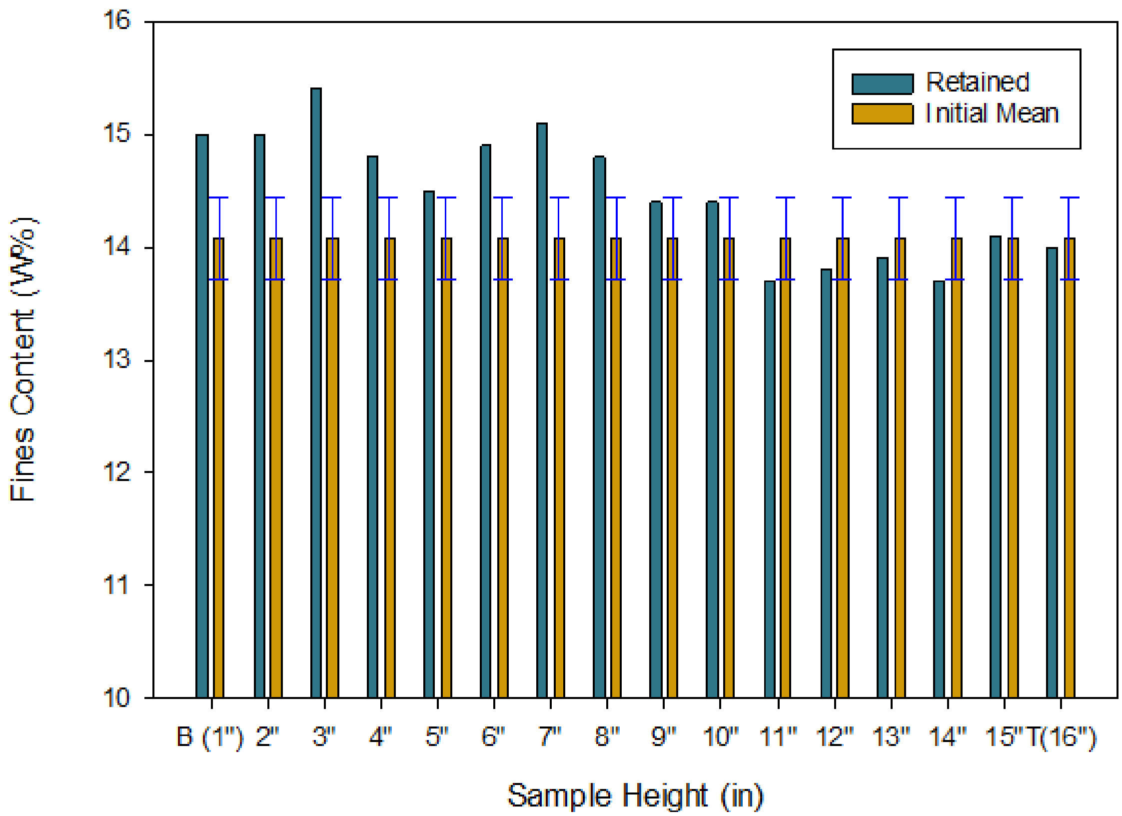

Figure 3. 9: Initial and retained fines content profile -Test No. 1.

3.5.2 *Test No. 2 (Wire mesh, DC-I sand, Hydrodynamic effect)*

This test aimed to investigate if the pressure drop behavior near the screen observed in Test 1 was mainly due to the slotted liner screen's low open area to flow (OFA). As a result, the test conditions for Test 2 were similar to Test 1, except using a coupon of the wire mesh screen with 37% OFA instead of the slotted liner screen with 1.3% OFA. Note that both screens' aperture size or slot width was 0.010 inches. As shown in **Figures 3.10-3.13**, similar trends as Test 1 were observed. Initial permeabilities at the low flow rate show a slight difference between intervals of the sand pack, which is unavoidable because of compaction error and random sorting of grains for each specific sample. Main flow test results indicated that the fines migration with the accumulation of fine particles near the mesh screen is responsible for the pressure drop behavior. Unlike Test 1, a higher maximum pressure drop (almost double) was observed for the bottom interval. The higher pressure drop can be attributed to the small size of openings for the wire mesh compared with the long slots in the slotted liner, which would result in more small pore throats at the interface of the screen. In addition, the higher dead-end area at the interface of the slotted liner and sand pack could also contribute as the retention of fine particles in these areas would not resist the flow paths. It can also be observed that the cumulative amount of the produced fines is slightly higher, which is justified by the high open flow area of the wire mesh screen.

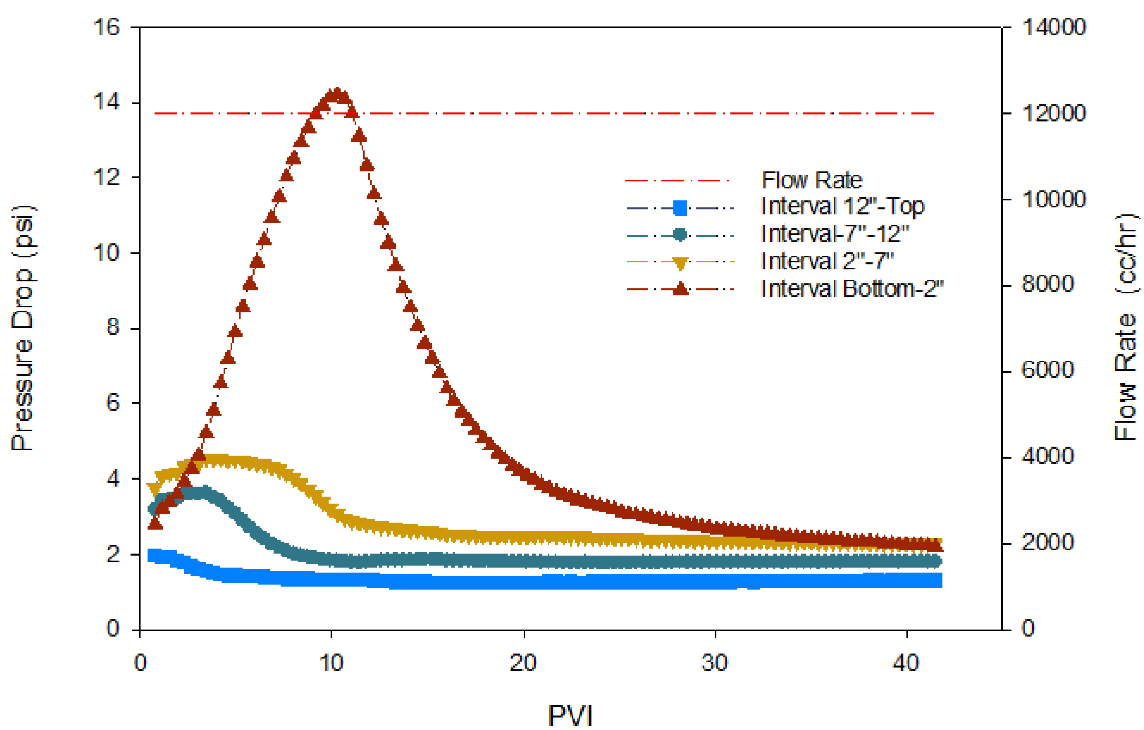

Figure 3. 10: Instant pressure drop variations at four intervals of the sand pack-Test No. 2.

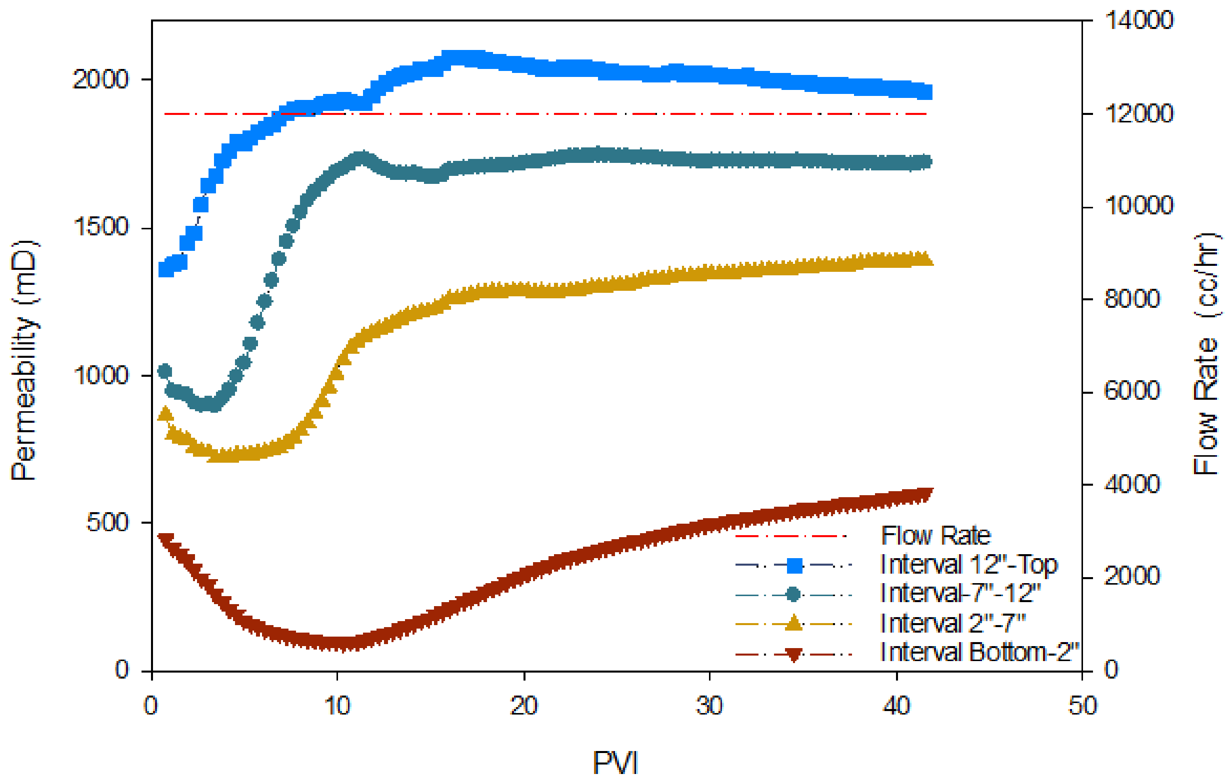

Figure 3. 11: Instant permeability variations at four intervals of the sand pack-Test No. 2.

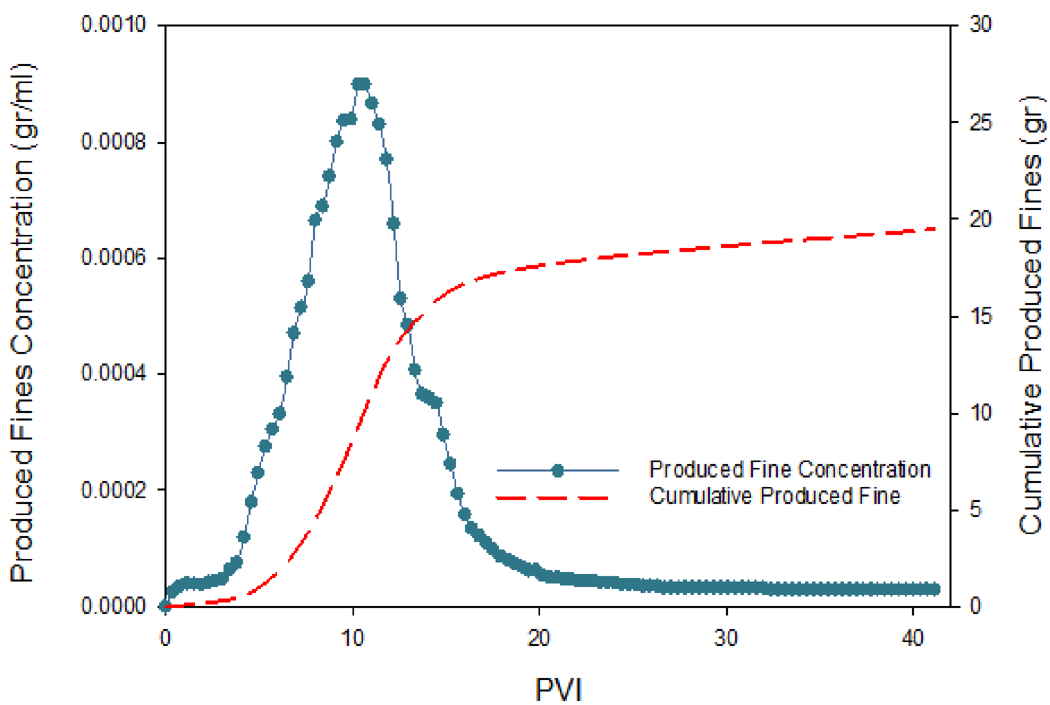

Figure 3. 12: Produced fines concentration versus injected pore volume -Test No. 2.

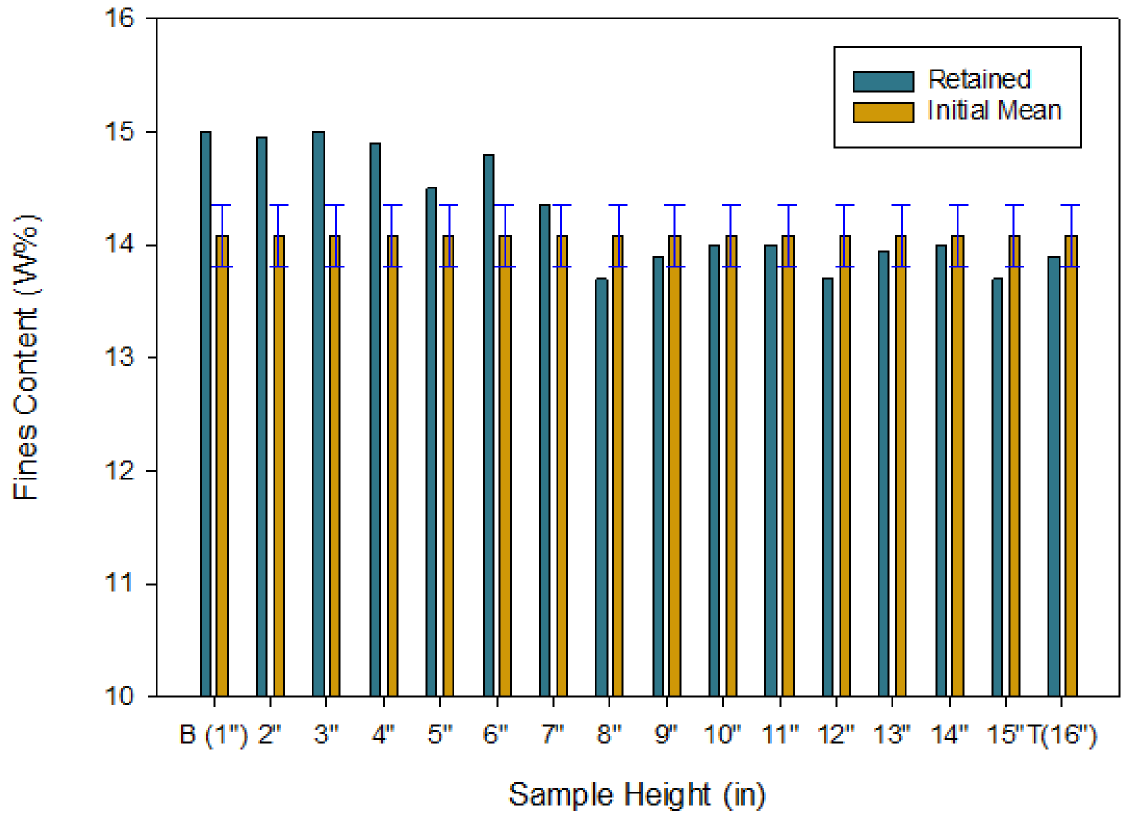

Figure 3. 13: Initial and retained fines content profile -Test No. 2.

3.5.3 *Test No. 3 (SL Coupon, DC-I sand, Particle size effect)*

This test was aimed to investigate if the pressure drops behavior could be governed by the size distribution of the fines fraction of the sand pack. Therefore, the test conditions were kept the same as Test 1, and just the fines fraction of DC-I sand was replaced with a uniform distribution of fine particles with sizes less than 2 μm. In addition, to avoid a significant reduction in the initial absolute permeability of the sand pack, a 6.0 wt% fines content was considered. It was expected that the released small fine particles could easily pass through the pore throats and produce out through the screen. Accordingly, it would lead to a monotonic increase in permeability.

As the results in **Figures 3.14 and 3.15** reveal, similar trends for the pressure drops and concentration of produced fine particles were observed. The results confirm that the concentration of the mobile fine essentially has a higher contribution to the pressure drop behaviors than the particle size distribution. In contrast to Test 1, much higher values for the maximum pressure drop and the cumulative amount of produced fines were recorded. The flat trend seen for the bottom interval in **Figure 3.14** is due to pressure drop values above 15 psi, out of the pressure transmitter range. The higher pressure drop for the bottom interval is attributed to the high concentration of small mobile fines particles migrated within the sand pack and arrived at the screen's sand retention layer. For the same reason, the cumulative amount of produced fine particles for this test **(Figure 3.15)** is higher than in Test 1 **(Figure 3.8)**.

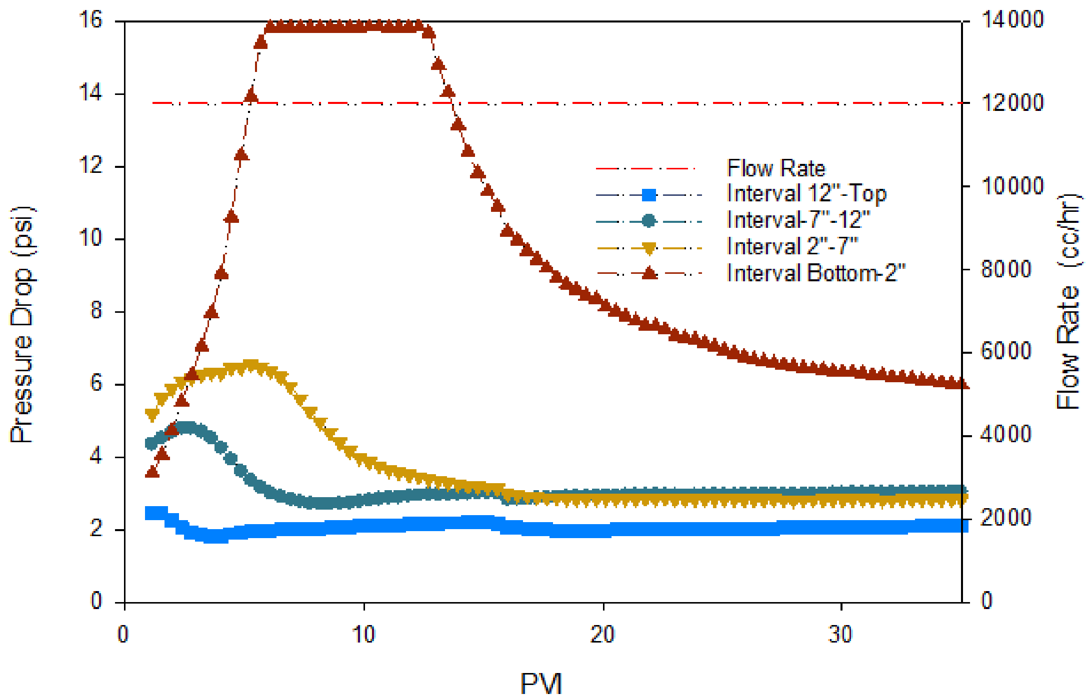

Figure 3. 14: Instant pressure drop variations at four intervals of the sand pack-Test No. 3.

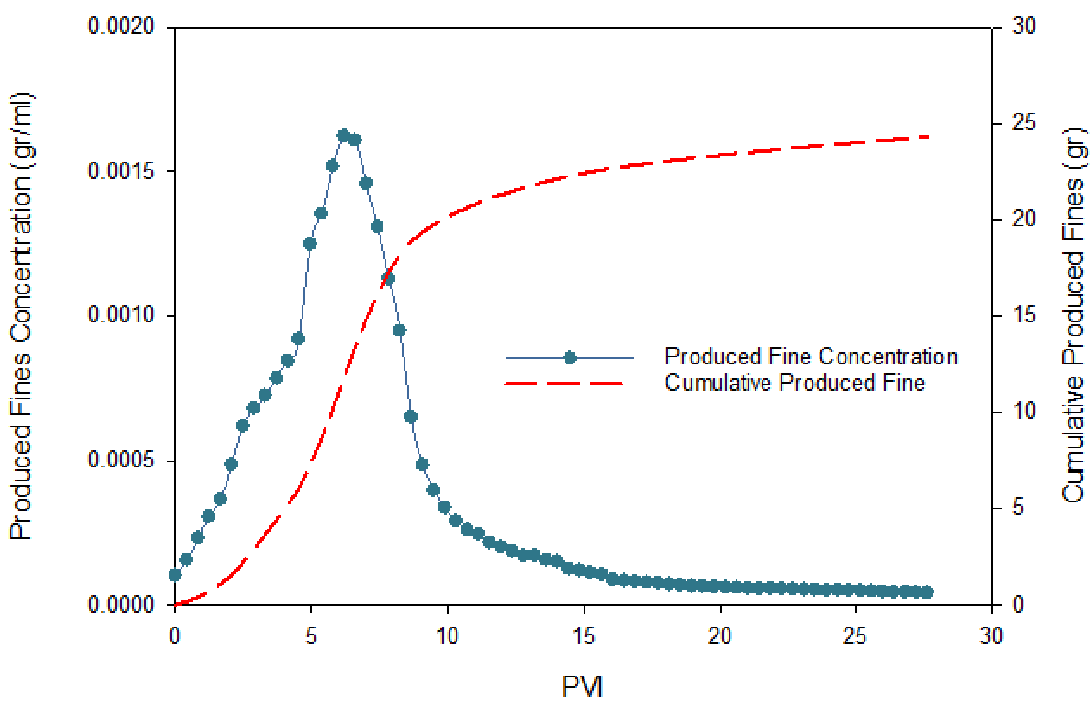

Figure 3. 15: Produced fines concentration versus injected pore volume -Test No. 3.

3.5.4 *Test No.4 (SL Coupon, DC-I sand, Chemical effect)*

The intention for this test was to release a high level of fine particles from pore surfaces by chemical effect. Thus, the sand pack was initially saturated with 400 ppm brine, and then deionized water (DI) was injected at a low flow rate of 2000 cc/hr. Here, the upper interval is a layer of coarse gravel to limit the total pressure drop within the sand pack. As shown in **Figure 3.16**, when the DI front reached the top of the sand pack, the pressure drop sharply increased to high values above the pressure transmitter range due to high mobile fines concentration. Subsequently, the sand pack was significantly plugged after a few pore volume injections even before the DI front arrived at the bottom interval. The results confirm that the fines migration in the field scale under conditions applied in this test would result in a complete plugging of the porous medium that masks the screen's flow performance. However, the absolute permeability of natural oil sands is usually high in the range of several Darcies, and a complete plugging is less likely. Unlike previous tests, the low flow rate of 2000 cc/hr is insufficient to remove initial fine particles at pore throats under hydrodynamic forces to increase sample permeability. Therefore, the released fine particles from pore surfaces under the chemical effect accumulate on pore throats and lead to a sharp increase in pressure drop.

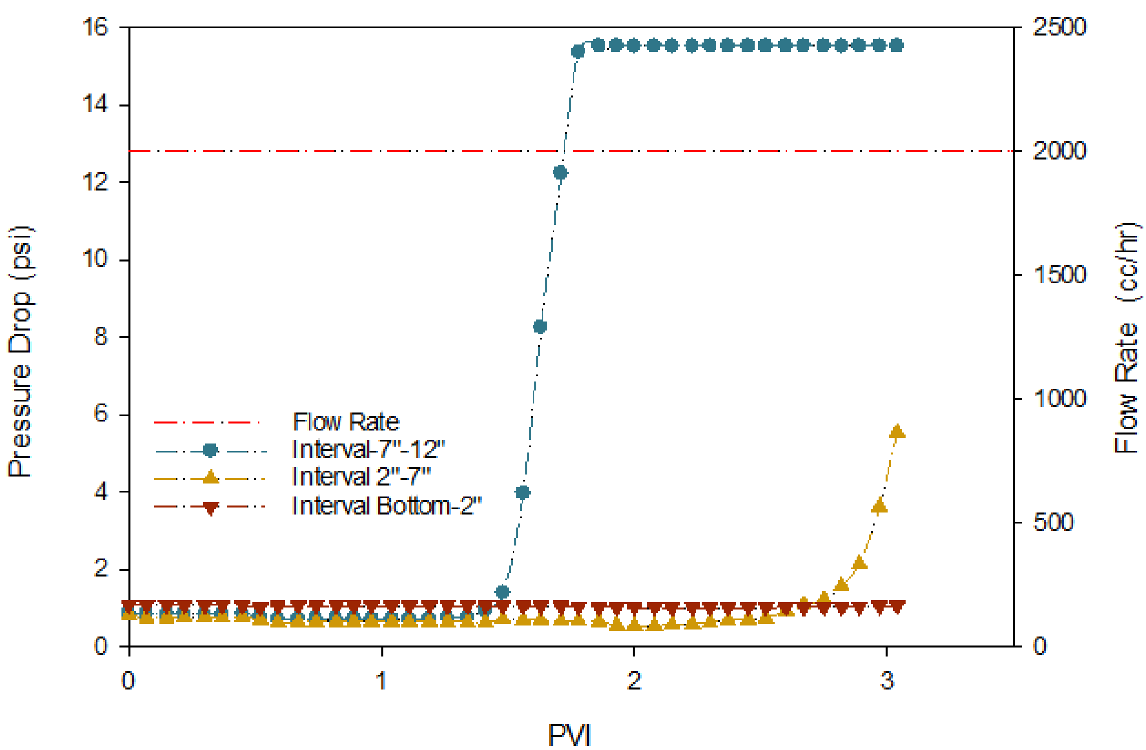

Figure 3. 16: Instant pressure drop variations at several intervals of the sand pack-Test No. 4.

3.5.5 *Test No. 5 and No. 6 (SL Coupon, DC-III sand, Hydrodynamic and Chemical effect)*

The distance away from the wellbore where fine particles are released and migrated toward the screen might be much longer than the sand pack length in the experiments. In other words, mobile fine particles would be arriving at the near screen zone for a longer time, increasing the probability of a monotonic permeability loss by pore plugging. It is not practical to thoroughly replicate this condition in the experiments. Attempts were just made to establish severe conditions concerning hydrodynamic and chemical effects for releasing high concentrations of fine particles. Therefore, these tests were conducted on relatively coarse, low fines content and short-length sand packs to investigate both hydrodynamic and chemical effects, considering the limitations of the setup. In Test 5, 400 ppm brine was injected at a flow rate of 16000 cc/hr as the first stage to release fine particles only under hydrodynamic forces. Then, the brine was displaced by deionized water at a lower flow rate of 2000 cc/hr to release fine particles by a chemical shock. **Figures 3.17 and 3.18** show the pressure drop and permeability behavior for both stages. It can be seen that the effect of the release mechanism on permeability is dominant at the first stage. As a result, the permeability is improved for both intervals of the sand pack. The upper interval has a monotonic increase in permeability, but the bottom interval shows a non-monotonic trend as in previous tests. For the second stage, the effect of plugging on permeability by a high concentration of mobile fine particles prevails over the effect of release. This observation implies that fine particles are mainly released from pore surfaces and low-velocity areas under chemical shock at the second stage, not significantly increasing the permeability. Instead, the high concentration of mobile fines plugs some thin pore throats by multi-particle bridging and accumulation mechanism. Because of a significant increase in permeability at the previous stage, the effect of the second stage on reducing permeability is not high, and final permeability is stabilized at relatively high values.

At the beginning of the second stage, the lower permeability values are because of the dependency of permeability to the flow rate for a range of low flow rates as observed in the tests. **Figure 3.19** shows the retention profile over the length of the sand pack after completion the Test 5. Because of the release of a high concentration of fine particles under chemical effect, a decreased fines content for all intervals of the sand pack is observed

In Test 6, a worst-case scenario for the fines migration process with combined hydrodynamic and chemical effects was considered. Therefore, after initial permeability measurements at low flow rates of 400 ppm brine, deionized water at a high flow rate of about 52,000 cc/hr, equivalent to a superficial velocity of 7.9 $\times 10^{-4}$ m/s was injected.

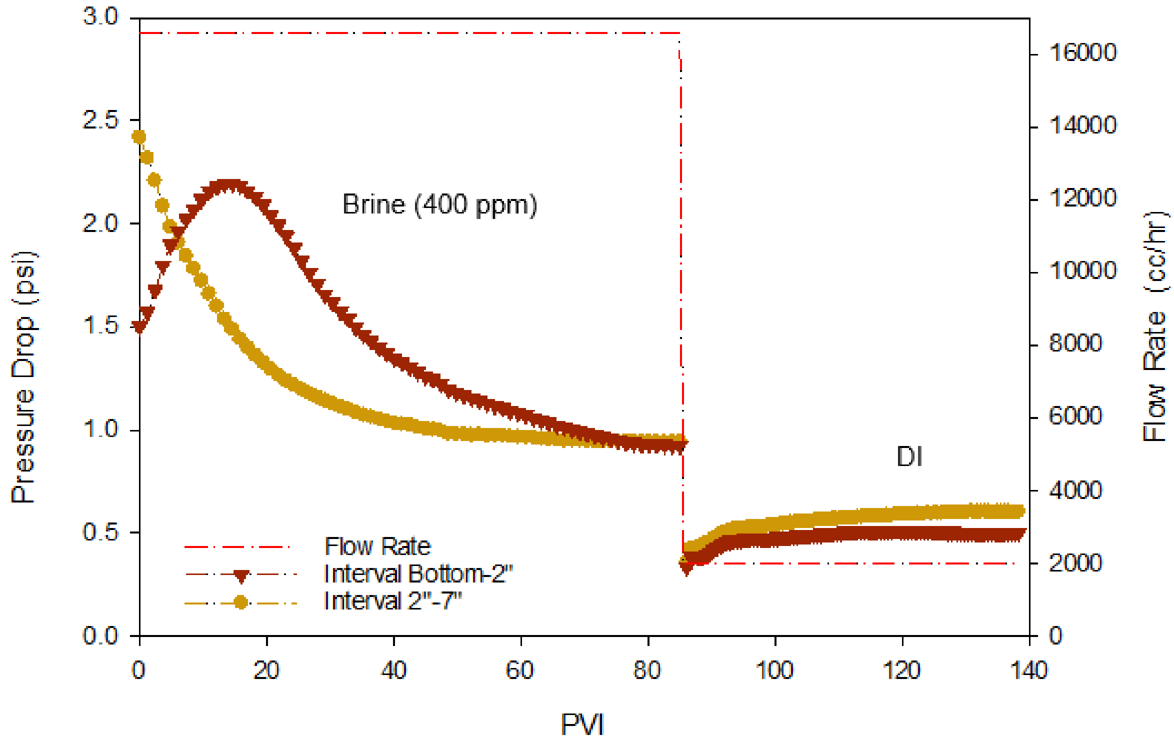

Figure 3. 17: Instant pressure drop variations at two intervals of the sand pack-Test No. 5.

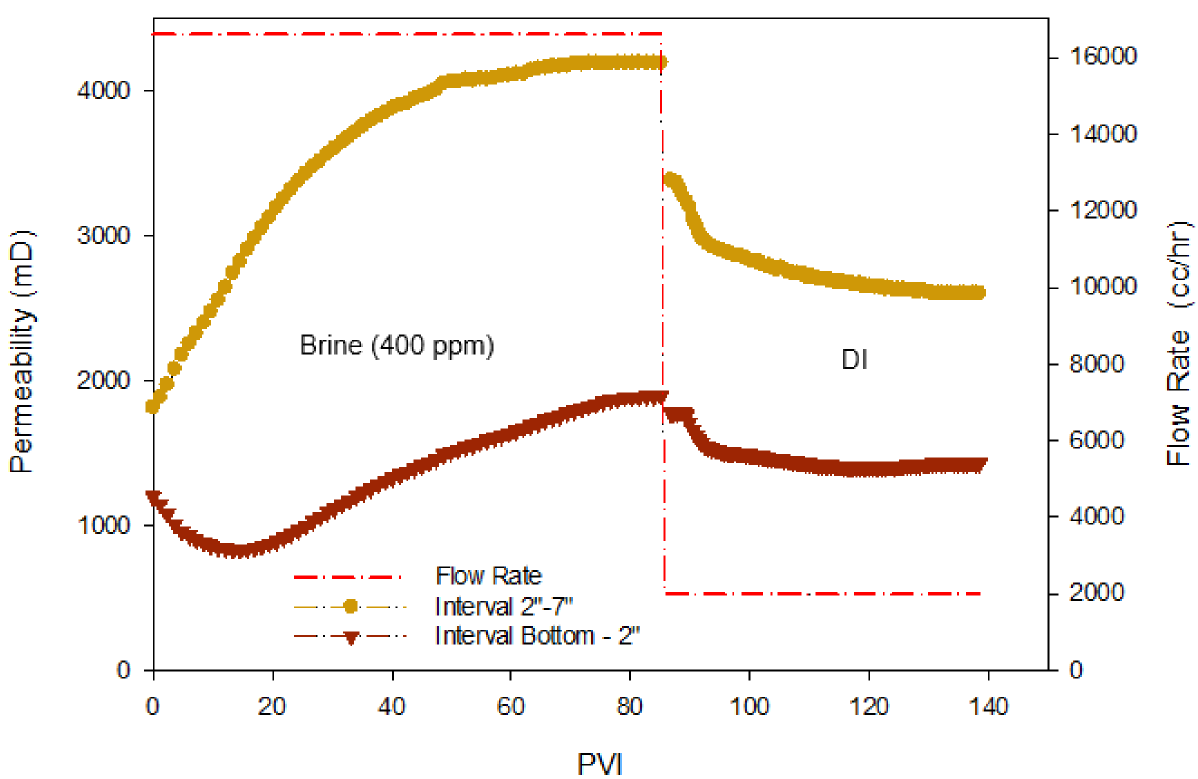

Figure 3. 18: Instant permeability variations at two intervals of the sand pack-Test No. 5.

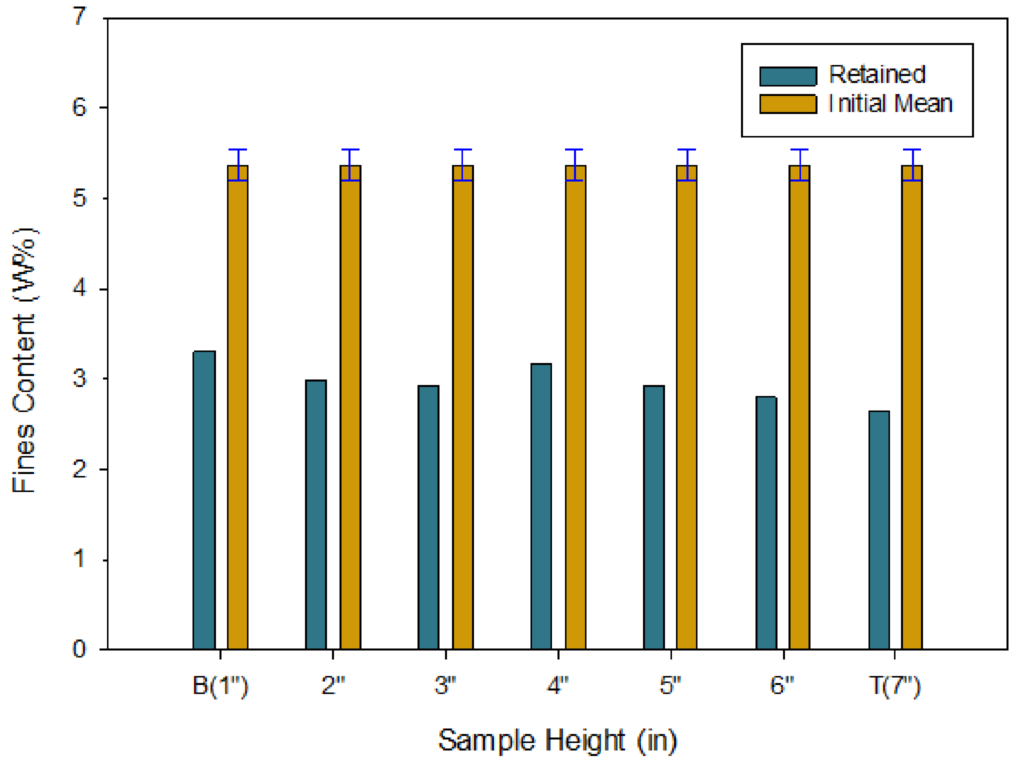

Figure 3. 19: Initial and retained fines content profile -Test No. 5.

As shown in **Figure 3.20**, pressure drop behaviors show a non-monotonic trend, improving permeability at later injection stages. In addition, it is observed that even with the high concentration of mobile fines due to the chemical shock, the effect of the release mechanism, especially sweeping fines at non-pluggable pore throats, prevails the plugging effect at the first pore volume injections. The maximum pressure drops values reveal that the precedent plugging effect is more significant in Test 6 than in Test 5 due to high mobile fines concentration and high superficial flow velocity. **Figure 3.21** shows the fines retention profile for Test 6, similar to Test 5, consistent with releasing a high concentration of fine particles under chemical effect.

As mentioned earlier, a significant increase or decrease in permeability was observed at the initial times of each stage when the flow rate changed in the tests. Several explanations or combinations of them may account for this observation. They include flow nonuniformity at low flow rates in a large-scale sample, significant change in effective stress due to pore pressure changes and low overburden stress (axial load), significant change in effective porosity with changes in the flow rate, and instant effect of the release of fine particles at pore throats. The latter cannot explain the permeability decrease at the second stage of Test 5 when the flow rate decreased. However, a separate test was conducted on a fines-free coarse sand pack similar to Tests 5 and 6 to investigate if fines migration had contributed to this matter. In addition, to investigate the flow distribution effect, pressure drops were also measured from pressure ports connected to points at the center inside the sand pack. From **Figure 3.22**, we can see that permeability increases linearly for the flow rates below a threshold and remains constant. Comparing sidewall and central pressure drop measurements in **Figure 3.23** shows a slight difference but similar trends.

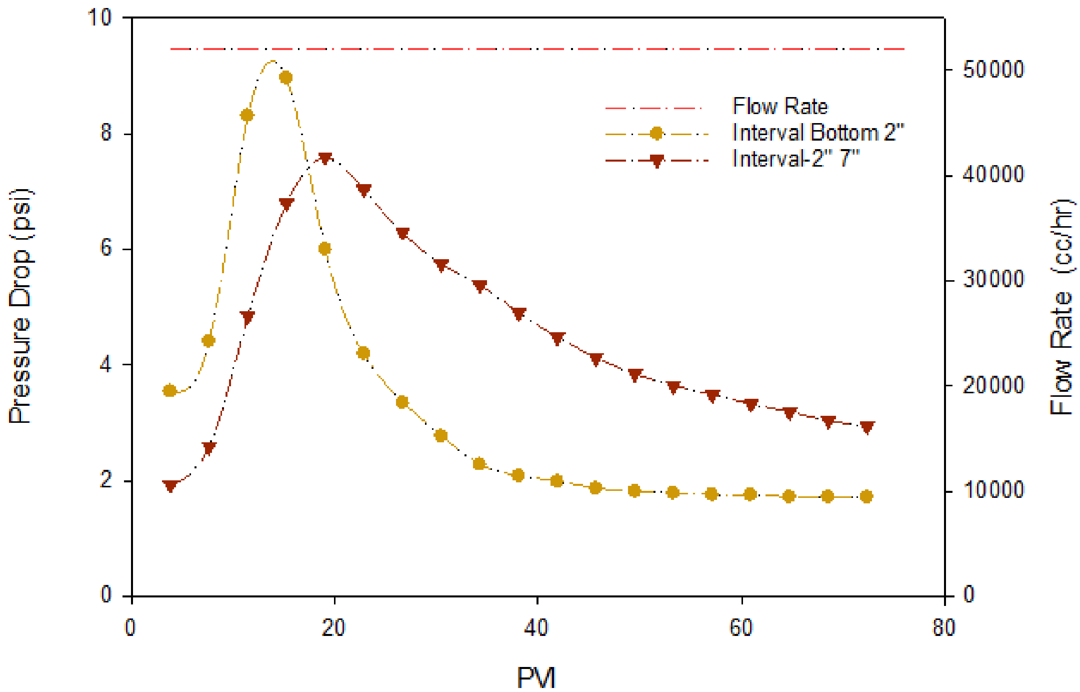

Figure 3. 20: Instant pressure drop variations at two intervals of the sand pack-Test No. 6.

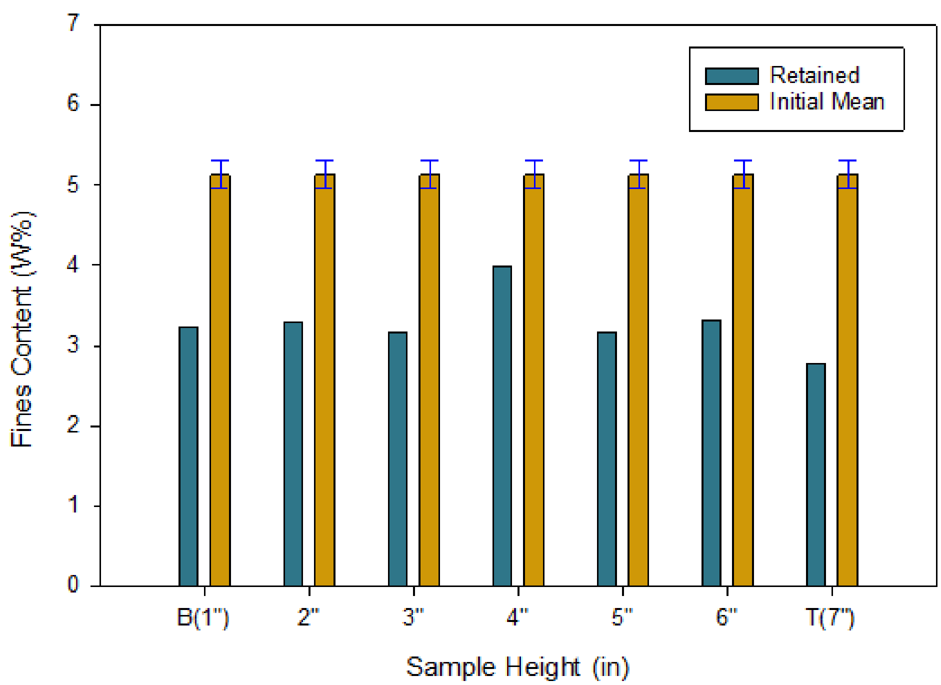

Figure 3. 21: Initial and retained fines content profile -Test No. 6.

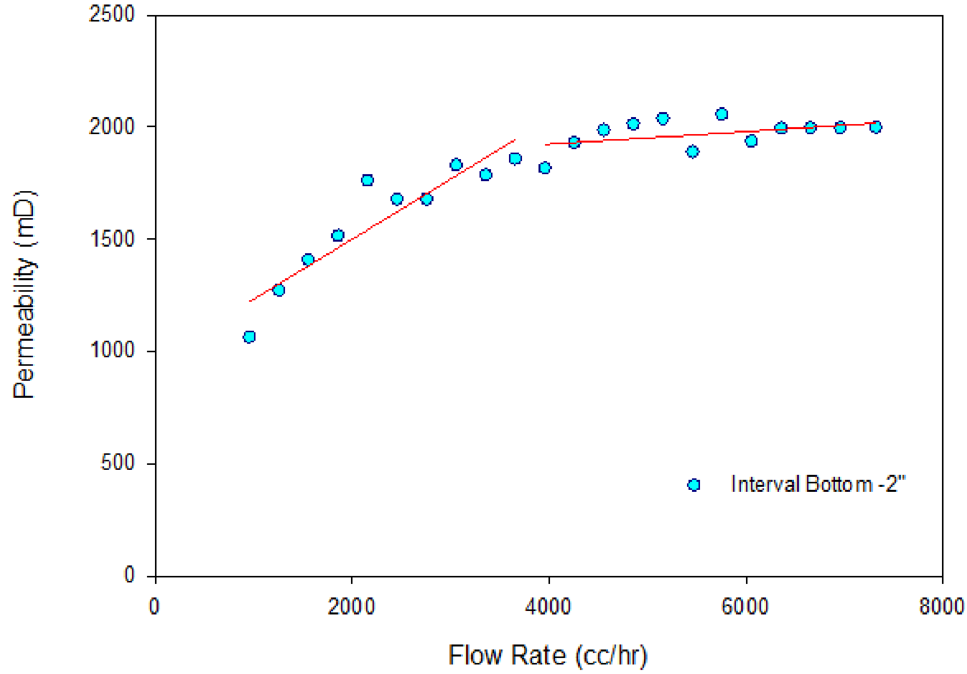

Figure 3. 22: Permeability variation with increasing flow rate -Bottom interval (0-2") of a fines-free sand pack.

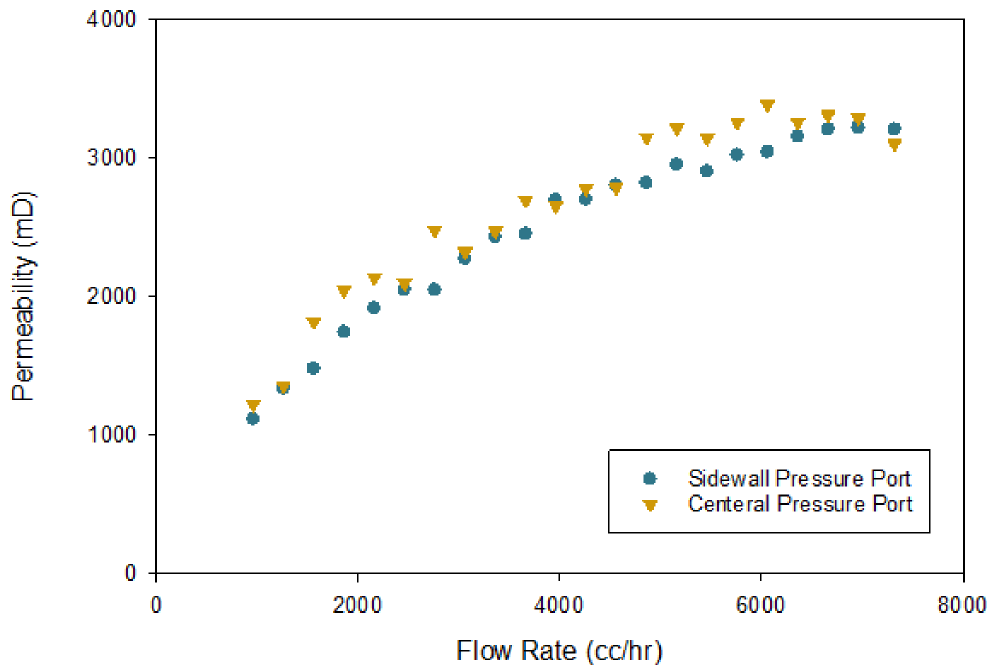

Figure 3. 23: Comparison of permeability variation with increasing flow rate based on the sidewall and central pressure transmitter ports.

An explanation for permeability variation with flow rate as one of the deviations from Darcy's law has been provided by Carman [39]. It is postulated that high surface tensions between liquid (water) and solid grains in a granular sand pack retain a stationary film or ring of liquid on grains' surface or contact points. An increase in flow velocity decreases the liquid film or ring size, increasing effective porosity and permeability. This effect would not be significant for very fine-grained sands and organic liquids with low surface tensions. It seems that the surface tensions between brine and commercial sand grains used in these experiments are high enough to promote this effect. However, this may not justify the significant difference in initial times permeability values observed in Tests 5 and 6 at high flow rates. Therefore, effective stress also has a considerable contribution here so that initial times permeability values for the bottom interval with high effective stress have lower variation than upper intervals. Anyhow, the observed results and trends are independent of the initial permeability, and the accuracy of the above observations remains.

3.6 Discussion on Reliable Testing Procedure

This study primarily intended to investigate the flow performance of sand control screens in SAGD wells under the fines migration process.

- *Are the standard SRT test results faulty?*

As observed in *Tests No. 1 to 5*, in contrast to previous sand retention testing observations, the sand control screens' retained permeability has a non-monotonic behavior (i.e., decreases and then increases) with time. Repeating the test under different situations proved this behavior to us. As a result, using the short-term retained permeability of the sand control screens would not be a reliable flow performance criterion to select the optimum design for formations with considerable fines content.

- *Suggestion of laboratory SRT procedure under fines migration*

Several field and laboratory observations confirm the loss of the permeability of the oil sand reservoirs around the SAGD wells under fines migration [40, 41, 42]. Core flooding tests conducted on actual oil sands with 10.0 wt% fines content resulted in a monotonic decrease in permeability under hydrodynamic and chemical effects of the fines migration for preserved and repacked samples [42]. The flow rates used to investigate the fines migration by the hydrodynamic effect were in the range of 4,000-20,000 cc/hr, comparable to what was applied here. In contrast, as presented above, current experiments mostly showed a non-monotonic behavior with final increased permeability values due to the dominant effect of the release mechanism in the fines migration process. This observation was found for the interval near the sand screen and other intervals of the sand pack.

Several factors control the permeability behavior under the fines migration process in porous media from extensive literature. These factors generally include the amount and concentration of mobile fine particles (depending on fines content, flow conditions, size of the porous medium from which fine particles are being released), particle and pore size distributions, and flow velocity. The difference in permeability behavior between current tests and the preserved core samples is most likely because of the difference in pore size distribution, the amount of mobile fine particles, and a considerable amount of swelling clays such as smectite, which initially reduce the effective flow area of the pore throats.

It would not be easy and practical to replicate in-situ pore size distribution and the extent of the damaged area around the wellbore by fines migration in laboratory tests. The results will be subjective and limited to customized worst-case scenarios for design purposes. However, to be consistent with field and core flooding observations, the testing procedure should lead to a monotonic decrease in permeability with time, as observed in the second stage of Test 5. This behavior would enable one to evaluate which design imposes a less permeability loss on a laboratory scale while having good sand retention performance. Indeed, that would be a relative laboratory-based evaluation under specific test conditions close to those in the field. Therefore, it seems that a test procedure similar to that applied in Test 5 would be proper. Since the initial loosely fine particles placed at pore throats of the synthetic sand pack will be removed under sufficient hydrodynamic forces, and at the second stage, the high mobile fines concentration by chemical shock will result in a monotonic decrease in permeability. At the end of the first stage, the sand pack properties represent better the natural formation. The second stage also represents a likely scenario of fines migration in SAGD wells with a chemical effect. As mentioned before, a more representative modification would be saturating the sand pack with high salinity brine (as formation brine) and injecting low salinity brine of 400 ppm (as produced brine).

- Lesson learned from laboratory SRT tests

There would be some sources of error for data analysis by studying the fines migration process in a large-scale sand retention setup. They include pressure pulsations at high flow rates, nonuniform sample mixture, inconsistent compaction for different intervals, and inaccurate measurements of produced fines and retention fines concentration. Therefore, a small diameter sand pack size would be beneficial to minimize the above errors, make uniform flow distribution, and facilitate conducting more tests with changing test parameters.

- Suggestion of numerical modeling

From laboratory evaluations, one could also determine a skin factor for the contribution of the sand screen to the permeability loss under fines migration. This skin factor can be incorporated into the well-scale numerical simulations to assess better the significance of the fines migration process on well productivity impairment.

3.7 Conclusion

In this study, for the first time, long-term tests (i.e., high pore volume injections) were performed in a large-scale sand retention testing set-up to study the phenomenon of fines migration and the flow performance of a sand screen. These experiments gave us an insight into the physics of the phenomenon and permeability behavior of a synthetic sand pack under the different rock and flow conditions, parts of which are summarized as follows:

(1) In contrast to previous sand retention testing procedures, the short-term retained permeability of the sand control screens would not be a reliable flow performance criterion to select the optimum design for formations with considerable fines content. The long-term fines migration process would result in a higher reduction in retained permeability and should be considered.

(2) A non-monotonic permeability behavior was observed with an initial decreasing trend followed by an increasing trend under the fines migration process for the interval near the sand screen.

(3) Different test conditions revealed that the release of fine particles near or from pore throats in non-pluggable pathways prevails the effect of straining and plugging of fine particles on thin pore throats at the first stage.

(4) The chemical shock effect significantly released fine particles and caused higher pressure drops in the sand packs. A monotonic decrease in permeability was observed under the chemical effect after the first stage of the fines migration caused by the hydrodynamic effect.

(5) The permeability behaviors following the previous test procedure at high pore volume injections were not consistent with field and actual core flooding observations, more likely due to unavoidable limitations concerning initial attachment of fine particles at pore surfaces, pore size distributions in a synthetic unconsolidated sample, and the amount of mobile fine particles as a function of time.

(6) A new test procedure representing worse-case flow conditions for the fines migration in the field resulted in a decreasing permeability behavior due to the high amount of mobilized fine particles and dominant retention mechanism.

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Chapter 4: Permeability Decline by Fines Migration Near Sand Control Screens in Unconsolidated Sands: A Numerical Assessment

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4.1 Preface

The near-wellbore permeability loss caused by the release and migration of naturally fine particles impairs the well productivity in oil reservoirs. The damage would be intensified in the presence of restrictions such as sand control screens due to retardation and accumulation of fine particles resulting from flow convergence and high volumetric flux.

This study focuses on the experimental investigation and mathematical modeling of the permeability impairment near the sand control screens under a representative fines migration process for the SAGD well conditions. For this purpose, the single-phase flow experiments were conducted on unconsolidated sand packs in a sand retention testing (SRT) setup. The testing used different sand screens and considered the chemical effect of the fines migration process and different salinity for the saturating brine and flowing fluid. A 3D numerical model incorporating governing equations of fluid and particle transport in porous media and an empirical permeability loss equation was established to simulate the fines migration process.

The results show that the sand screens with a low open flow area and narrow aperture size cause higher permeability loss under the same flow conditions. Higher salinity reduction yields higher mobilized fines concentration, causing high near-screen permeability loss. A good match was obtained between the measured and calculated dimensionless pressure drops from the experimental and numerical models. The calibrated model could predict the dimensionless pressure drops for the near-screen interval with good accuracy. It was confirmed that the porous medium's model parameters were nearly independent of the sand screen. However, different results were obtained for different salinities, confirming the parameters' dependency on not just porous medium but also fluid properties.

4.2 Introduction

Fines migration has been well studied as one of the most crucial permeability loss mechanisms in natural reservoirs induced by one or both chemical and hydrodynamic effects of flow [1-4]. The process includes release (detachment) of fine particles from pore surfaces, transport and capture (deposition) of fine particles at thin pore throats, where most pressure drops and local permeability impairment occur at the pore scale [4, 5]. Fine particles tend to move with the wetting fluid [6], as quartzitic fines and clay minerals are usually water-wet [3] and migrate when water is mobile.

Previous works confirmed the existence of a critical flow velocity and salt concentration at which net forces on fine particles become repulsive, and the fine particles start to release [7, 8].

Both kinetic and equilibrium models for the release mechanism have been introduced in the literature. Kinetic models consider salinity effects on repulsion and the difference between the current and critical flow velocity as driving forces that reduce fines attachment over time [9, 10]. The equilibrium model considers a maximum retention concentration based on torque balance between drag, lift, and surface forces applied to the fine particles on pore surfaces [11]. Thus, the concentration of the mobile fines at the beginning of the process is the difference between initial and maximum retention concentrations. This approach is capable of simulating fast or instantaneous release cases with abrupt changes in bulk flow velocity and salinity, resulting in a rapid decrease in permeability as observed in laboratory tests [4, 12]. The capture mechanism is usually long-lasting and described by the kinetic expressions that relate the capture rate to the volumetric flux of mobile fines reaching the pore throats and available pore space or porosity [10, 13].

The laboratory-based mathematical modeling and upscaling is the most frequently used method to simulate the process and predict the permeability loss by fines migration at the wellbore scale [14]. This approach captures the local retained fines concentrations and their impact on the permeability in a continuum model. The set of governing equations includes the momentum equation for flow described by Darcy's law, the mass balance of mobile fine particles described by a convection-dispersion equation, macroscopic rate equations for release and capture mechanisms as the source and sink terms, respectively, and an expression for the permeability variation as clogging model [3,4,14-16] The model incorporates some parameters related to the porous medium and flow properties that can be determined directly from experiments or by matching the experimental observations.

Most previous modeling works were performed on natural consolidated formation cores with few cases on synthetic unconsolidated sands [1,3,7,9,14-17]. However, none of the past works incorporated and investigated the role of the sand control screen on the permeability loss by fines migration at the wellbore vicinity in unconsolidated formations. This critical consideration has been adopted in the present work focusing on fines migration in SAGD well producers drilled horizontally in unconsolidated oil sands.

Figure 1 shows Scanning Electron Microscopy (SEM) photographs of oil sands core samples from a SAGD well in Cold Lake, Alberta, before and after steam injection. The images indicate pore throat plugging by fines migration [18]. Oil sands are typically high permeable with several Darcy permeability; However, equivalent screen permeabilities are in the range of thousands of Darcies. Therefore, the retention of sand over the horizontal screen would not create a significant pressure drop at the near-wellbore. However, fines migration with relatively high mobile fines concentration flowing toward the screen can create large pressure drops due to fines accumulation near the screen. The retention mechanisms such as inertial retardation and direct interception caused by flow convergence and high flow velocity would facilitate the capture and bridging of fine particles near the screen [19].

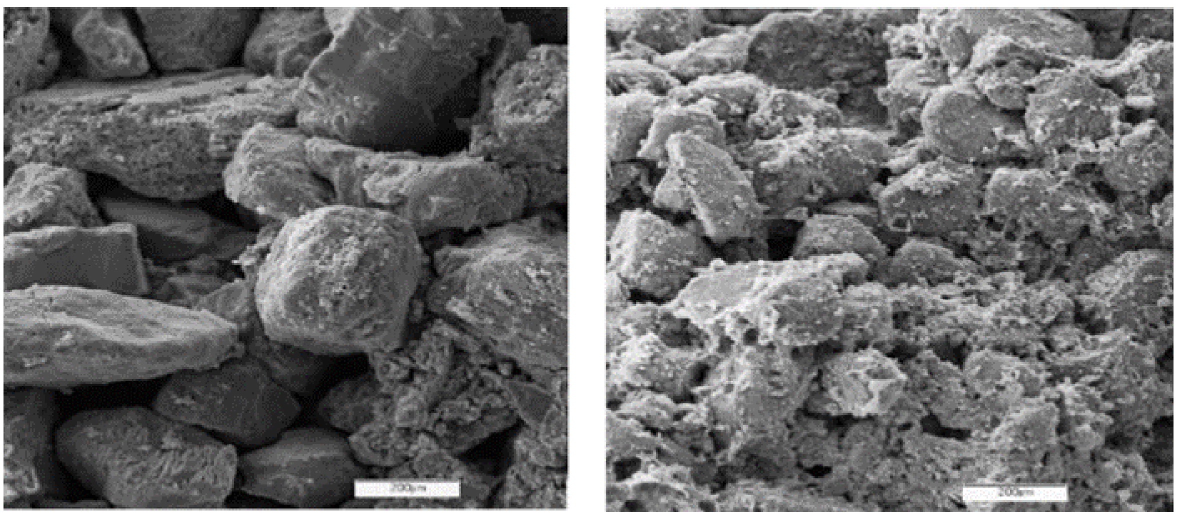

Figure 4. 1: Port throat plugging of oil sand core before (a) and after (b) steam injection (courtesy of SPE [18]).

Previous tests suggest that fines migration under typical SAGD flow rates would not yield significant pressure drops [20]. The present study examines fines migration in SAGD conditions and considers the chemical effects caused by low-salinity steam condensate in contact with high salinity formation brine near the SAGD production well. The primary objective is to develop a porous medium-sand control screen interaction model, simulating the fines migration process in a three-dimensional numerical model.

4.3 Experimental setup and results

4.3.1 Experimental Setup

This study used a sand retention testing (SRT) setup [20-23] accommodating sand control screen coupons for the fines migration study. This setup was designed to facilitate long tests, minimize pump fluctuations, increase sand pack and flow uniformity, and measure accurate pressure differentials. A photograph of the cell (ID 2.5", length 12") with pressure ports and a loading system is shown in **Figure 2(a)**. The sand sample was prepared using commercial sands, silts, and clays based on particle size distribution (PSD) of a sand class (DC-I) with 14.5 w% fine particles in the McMurray formation, Alberta oil sands [24]. A length of 4.5" sand sample was packed over the sand control screen mounted at the bottom of the cell to reach a target porosity of 37% by applying a wet packing procedure. The remaining length of the cell was filled up with coarse gravels to reduce flow disturbances and provide uniform flow toward the sand sample from the top. The sample was saturated from the bottom at a low flow rate of about 100 cc/hr with the help of a back pressure column that could provide a constant pressure of about 2.0 psi at the outlet during the flow tests.

(a) (b)

Figure 4. 2: (a) Photograph of the testing setup and sample cell, (b) taking 1-inch sand slices after the test.

Four pressure transmitters with a maximum 15 psi pressure range (± 0.035 psi accuracy) measured the differential pressures at first and second 2.0" intervals near and away from the sand screen and absolute pressures at 6.0" height and the inlet. An axial load of 200 psi was applied to prevent sand fluidization flow channeling and minimize effective stress variations during the fines migration process. Produced fines concentration was measured by taking fluid samples at the sample bottom, right below the sand screen, using a turbidimeter up to 3000 ppm. After completing the tests, sand samples were obtained from every 1-inch and top 0.5" intervals **(Figure 4.2b)**. The samples were washed on a 44-micron sieve and dried to determine the remaining fines content weight and PSD.

4.3.2 Testing Procedure

The testing procedure **(Figure 4.3)** used representative flow conditions in SAGD production wells.

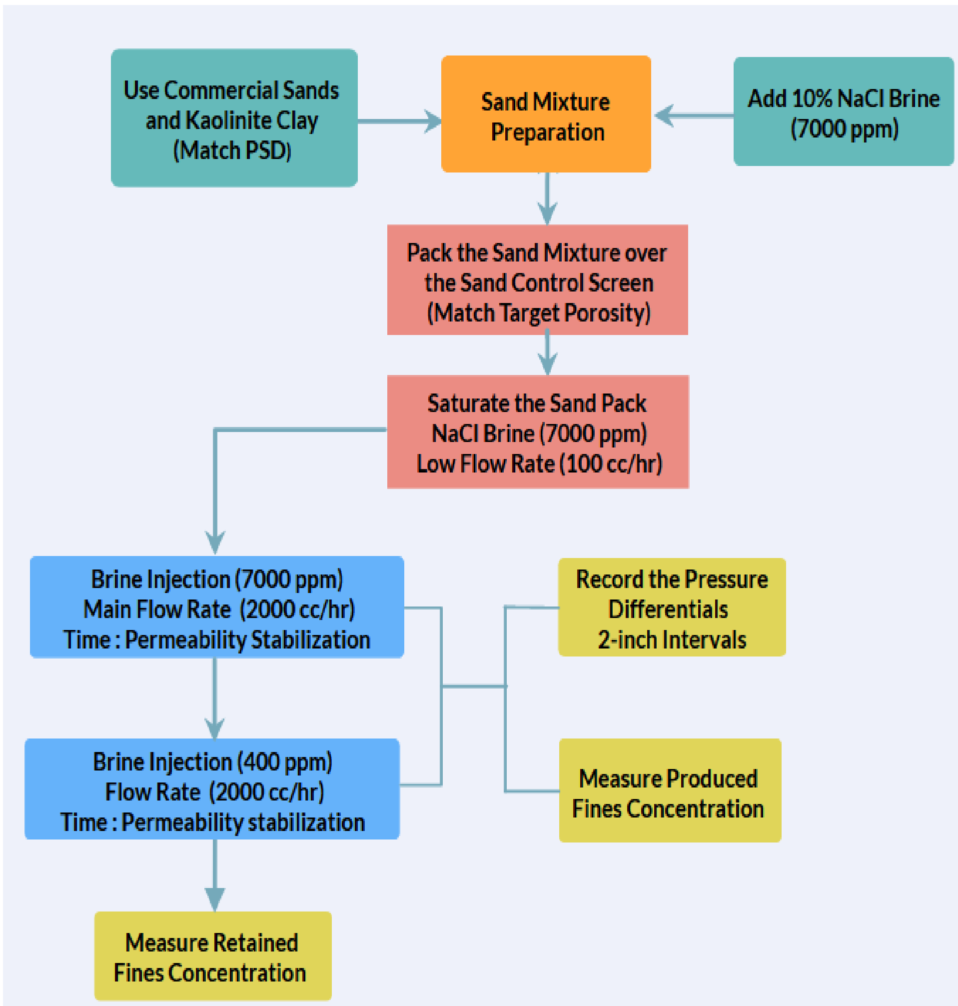

Figure 4.3: The testing procedure flowchart.

In this work, three Slotted Liner (SL) coupons were tested with the same slot density (number of slots per foot of pipe) and aperture size 0.010", 0.014", and 0.018", yielding an open flow area (OFA) of 1-1.5%. Additionally, screens with a higher open area such as Wire Wrapped Screen (WWS) with aperture size 0.015" (OFA 15%) and wire mesh with aperture size 0.010" (OFA 35%) were examined for comparison. To evaluate the salinity effect on mobilized fines concentration, the high salinity saturation brine (7000 ppm) also decreased to three low-level salinities of 800 ppm, 400 ppm, and 200 ppm in separate tests during the flow phase. NaCl is the prominent mineral salt of the produced water in the SAGD wells, with salinity ranging from 400 to 3000 ppm [25]. A worst-case trial of changing salinity to deionized water resulted in severe permeability damage to the whole sample.

4.3.3 Experimental Results

According to the geological description of oil sands, fine particles are mostly attached to the pore surfaces around a film of formation water [26]. However, because of the synthetic sand sample used in experiments, some insignificant fine particles might initially reside at pore throats or suspend during saturation. Results show that the first flow stage sweeps these particles from the sample under the hydrodynamic flow effect and stabilizes the sample's initial permeability in the range of representative high absolute permeabilities for oil sands. For example, **Figure 4.4** shows the variation of dimensionless pressure drop, defined as pressure drop divided by the initial pressure drop, for the first stage of the test using a wire mesh screen. Similar behavior was observed in all tests. Negligible cumulative produced fines concentration was observed at this stage.

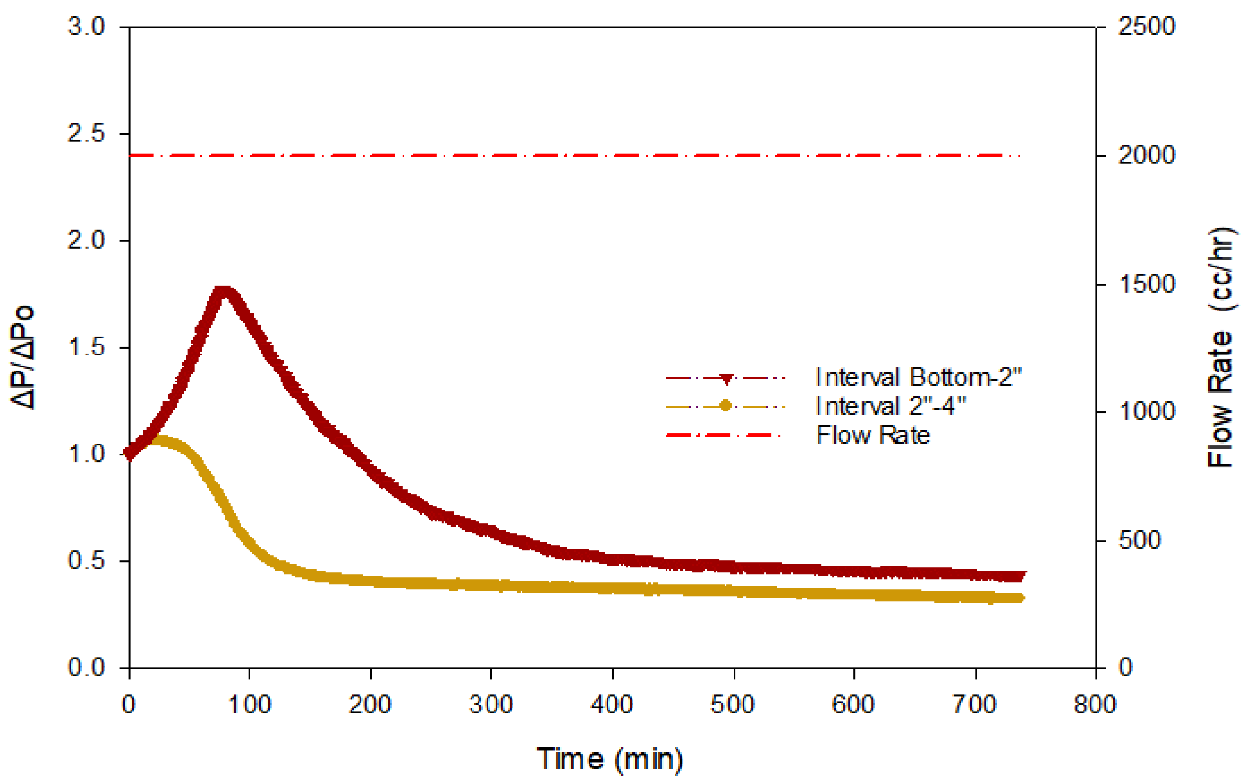

Figure 4.4: Dimensionless pressure drop variations for the first flow stage using a wire mesh screen.

Figure 4.5 shows the dimensionless pressure drop variations for the first stage of the test using the slotted liner coupon with 0.018” slots. A comparison of **Figures 4.4** and **4.5** indicates a higher pressure drop at the bottom interval than the top interval for the slotted liner, mostly because of flow convergence near the slotted liner. Low flow rates of about 400 cc/hr (not shown) resulted in no pressure drop variations.

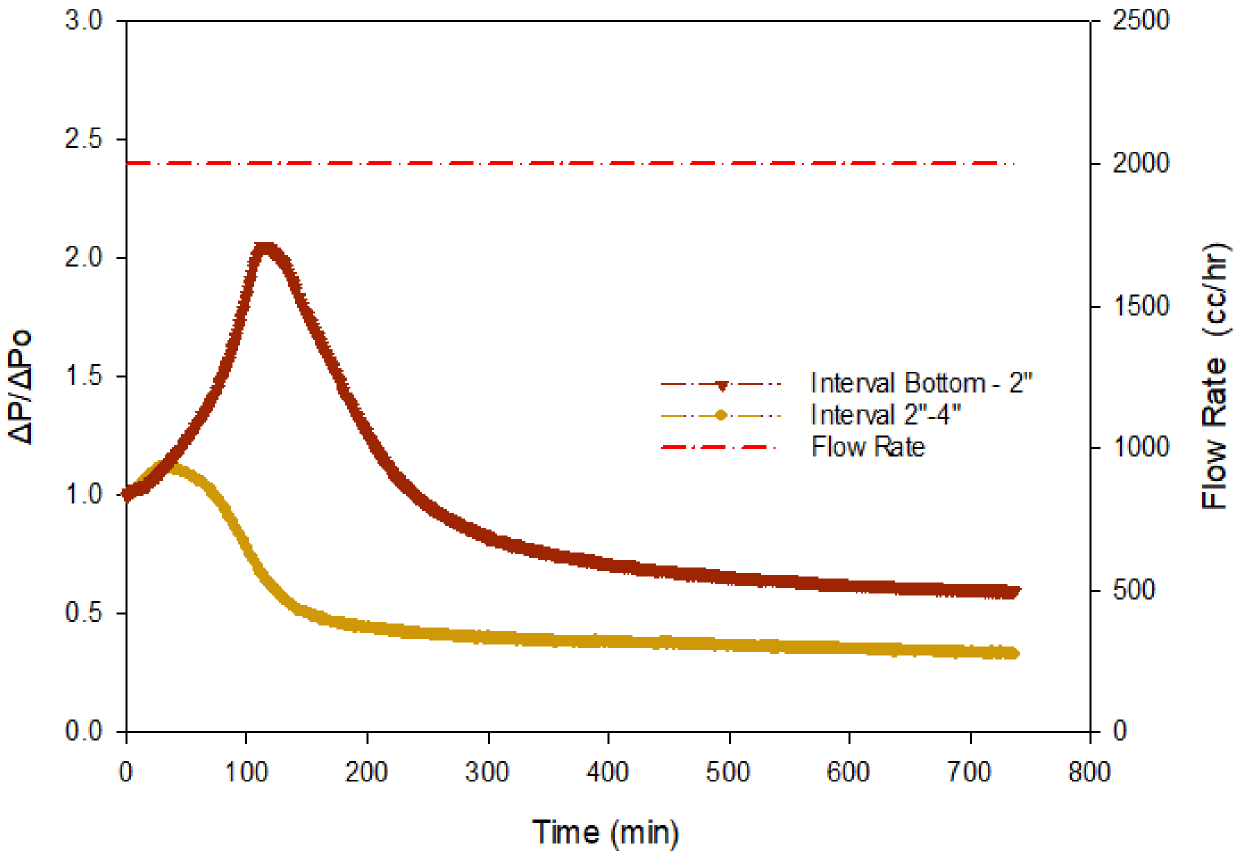

Figure 4.5: Dimensionless pressure drop variations for the first flow stage using SL 0.018" screen.

The second flow stage induces fines migration under chemical effects by injecting low salinity brine. **Figure 4.6** shows pressure drop variations near the screen for different SLs when salinity changes to 400 ppm. As expected, the screen with a smaller aperture experiences a higher pressure drop attributed to the high retention of mobile fines near the screen. As shown in **Figure 4.7**, a higher reduction in salinity caused higher pressure drops due to the high level of fines migration. From **Figure 4.8**, it is concluded that the high open flow area screens would yield slight pressure drops due to low fines retention concentration near the screen by small flow converge effect.

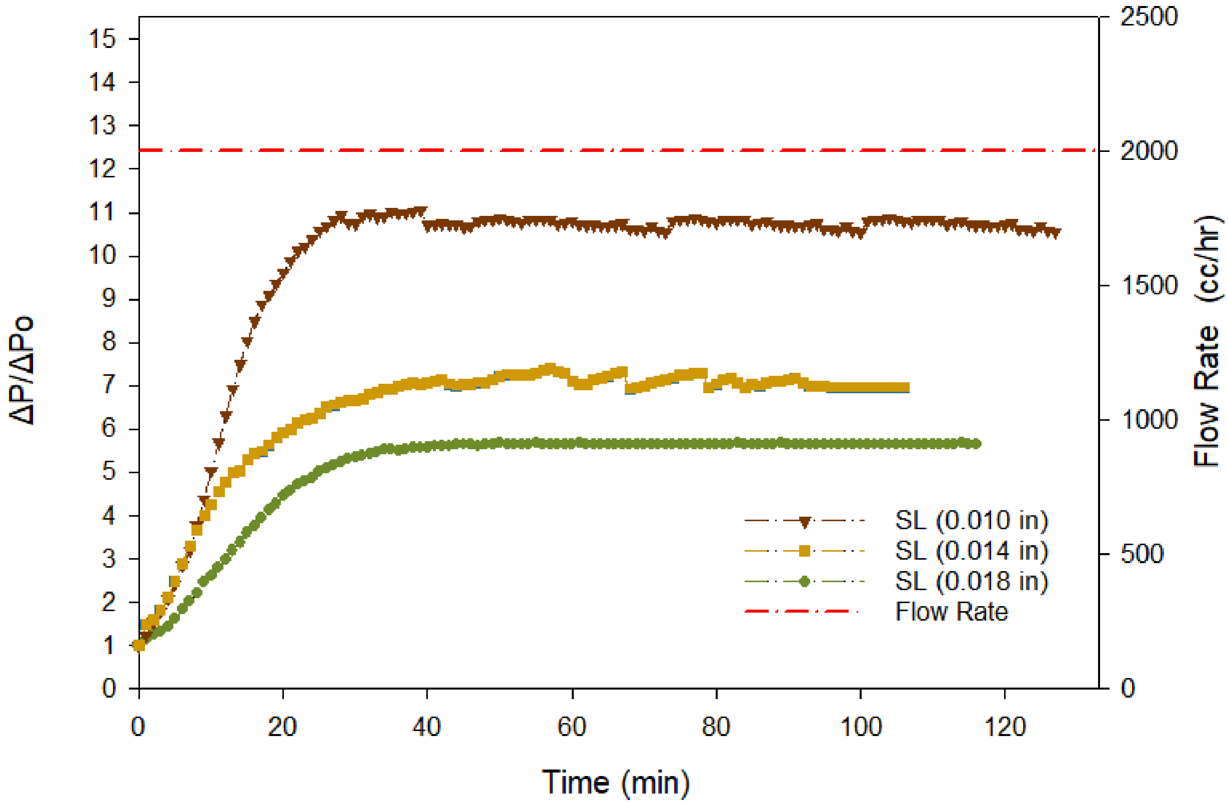

Figure 4.6: Near-screen dimensionless pressure drop for different SL screens, injecting 400 ppm brine.

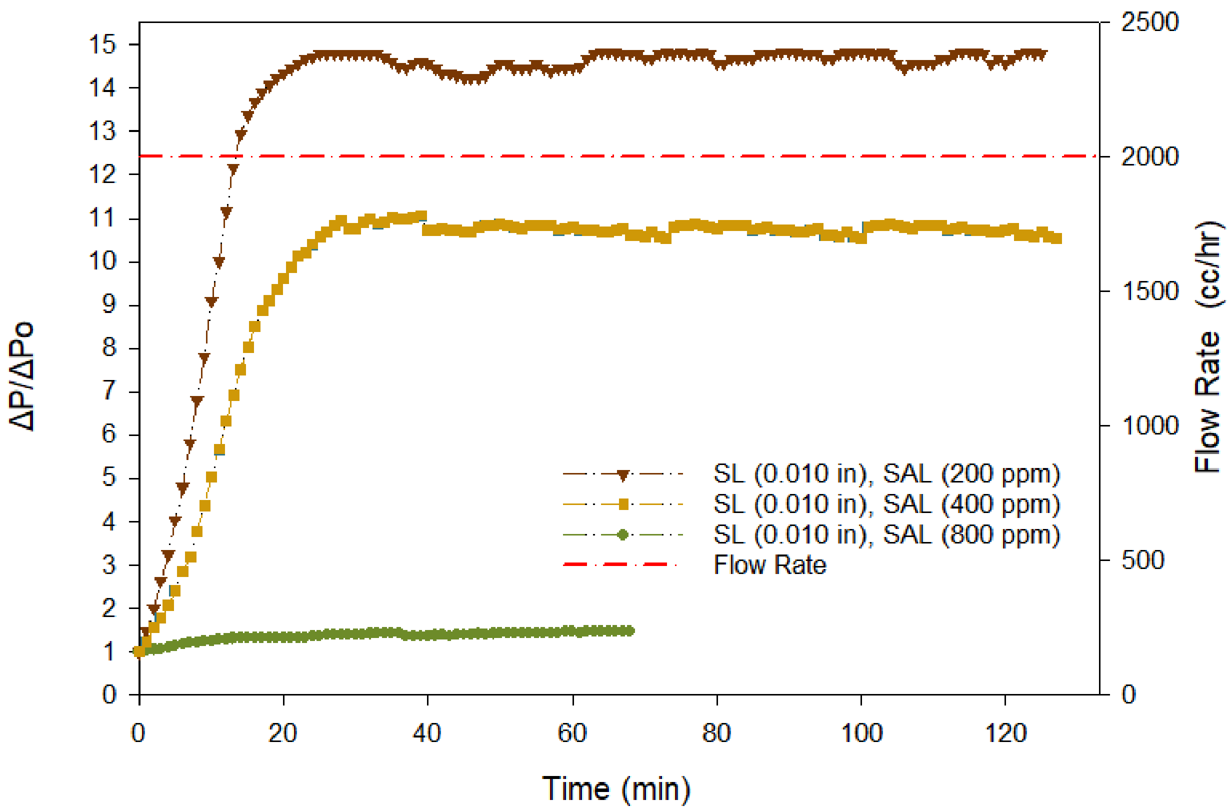

Figure 4.7: Near-screen dimensionless pressure drop variations for different brine salinity.

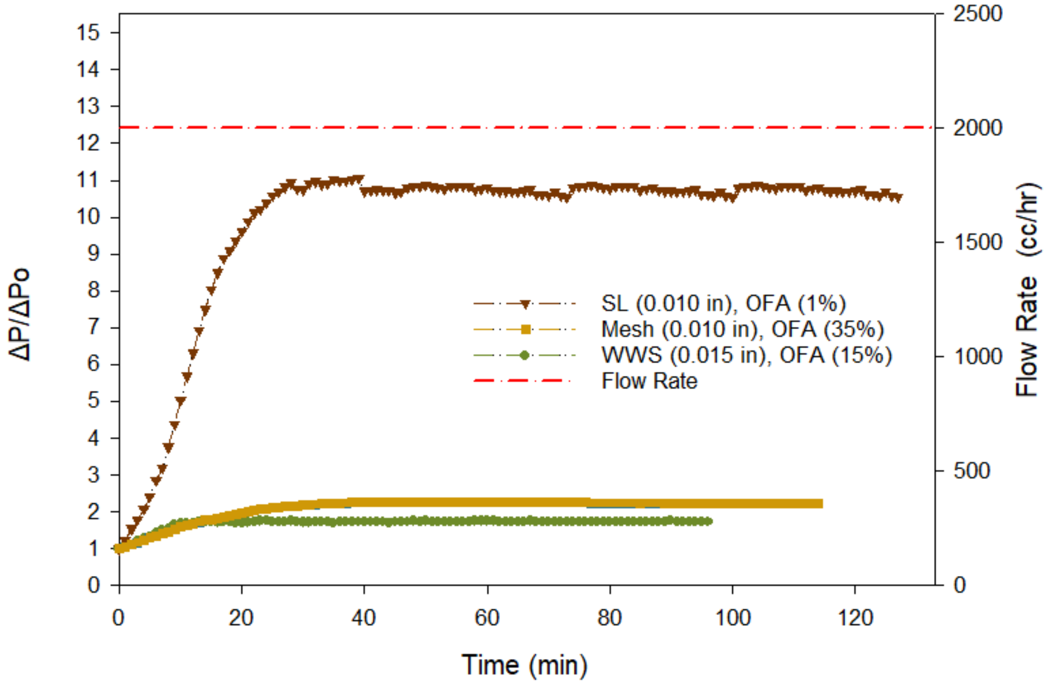

Figure 4.8: Near-screen dimensionless pressure drop for different sand screens, injecting 400 ppm brine.

In all tests, the pressure drop variations **(Figure 4.9)** for the second 2.0" interval away from the converging flow region were small, since released fine particles could easily migrate through a high permeable porous medium. Only a permeability loss of up to 15% was observed for the top 2.0" interval. In contrast, the near-screen zone encountered high permeability losses of up to 85%.

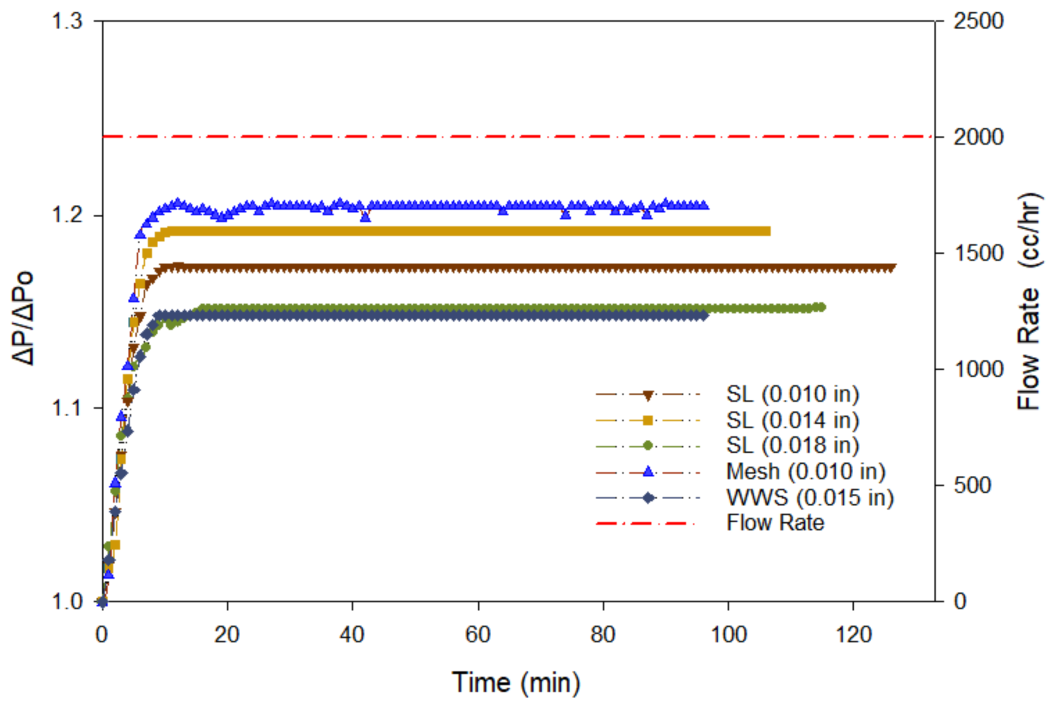

Figure 4. 9: Dimensionless pressure drop of the second 2.0" interval (away from the screen) for different sand screens, injecting 400 ppm brine.

Figure 4.10 shows sample results for instantly and cumulatively produced fines concentration during the test using SL 0.010" and salinity 400 ppm. Data has been averaged over every five minutes. Values beyond the range of turbidimeter are extrapolated by looking at the data trend to obtain an upper estimate of the produced fines mass. The extrapolated trend is based on the previous tests where the peak of the produced fines concentration was in the range of the turbidimeter. Also, assuming an instantaneous release mechanism and knowing the mass concentration of the released fine particles at the top 0.5" interval (from the mass concentration of initial fine particles and the retained fine particles at the end of the test), the estimated peak value could be between 0.006 g/ml and 0.007 g/ml to give a reasonable cumulative produced fines mass.

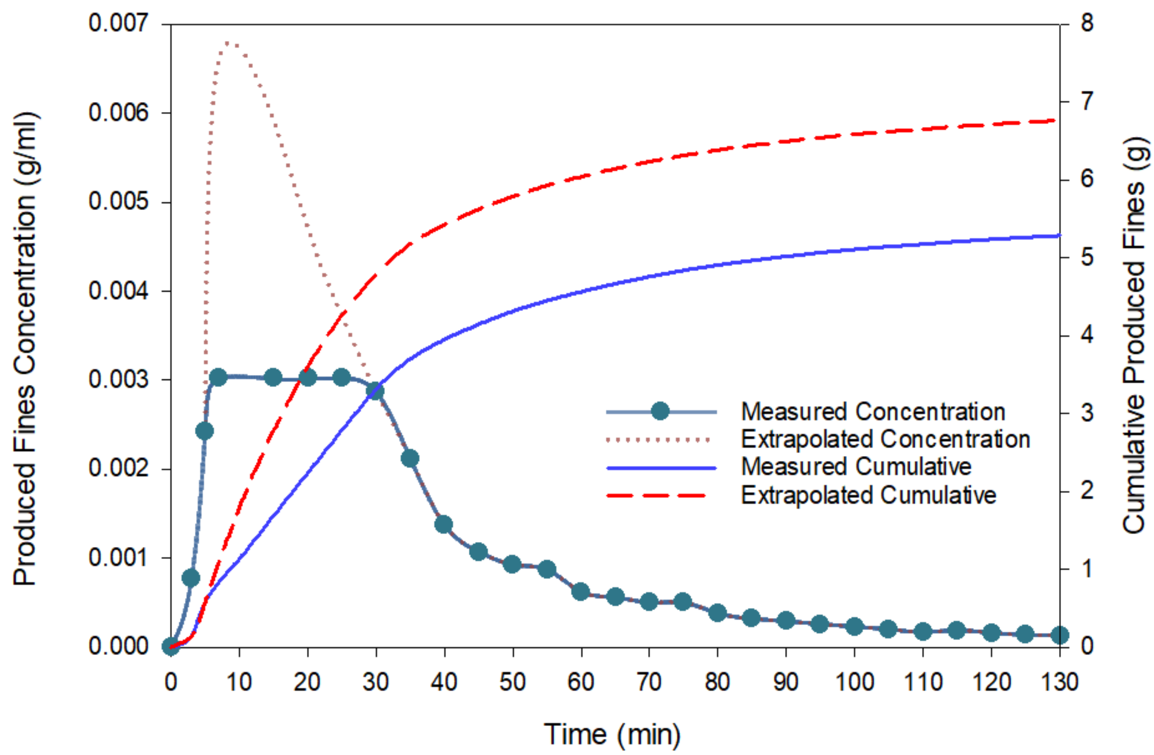

Figure 4. 10: Measured produced fines concentration for the test using SL 0.010" and injecting 400 ppm brine.

Figure 4. 11 presents the comparison between initial and retained fines content at different heights of the sand sample under the fines migration process by injecting different brine salinity. Assuming an instantaneous release mechanism and negligible retention for the top 0.5" interval, about 3.5 w% (2.9 g), 8.0 w% (6.7 g), and 11 w% (9.3 g) of initial fines mass (84 g) were produced at salinities 800 ppm, 400 ppm, and 200 ppm, respectively. The results are aligned with the cumulative produced fines graph, indicating that small retention of fine particles at the pore scale could have impaired the permeability and caused the observed pressure drops.

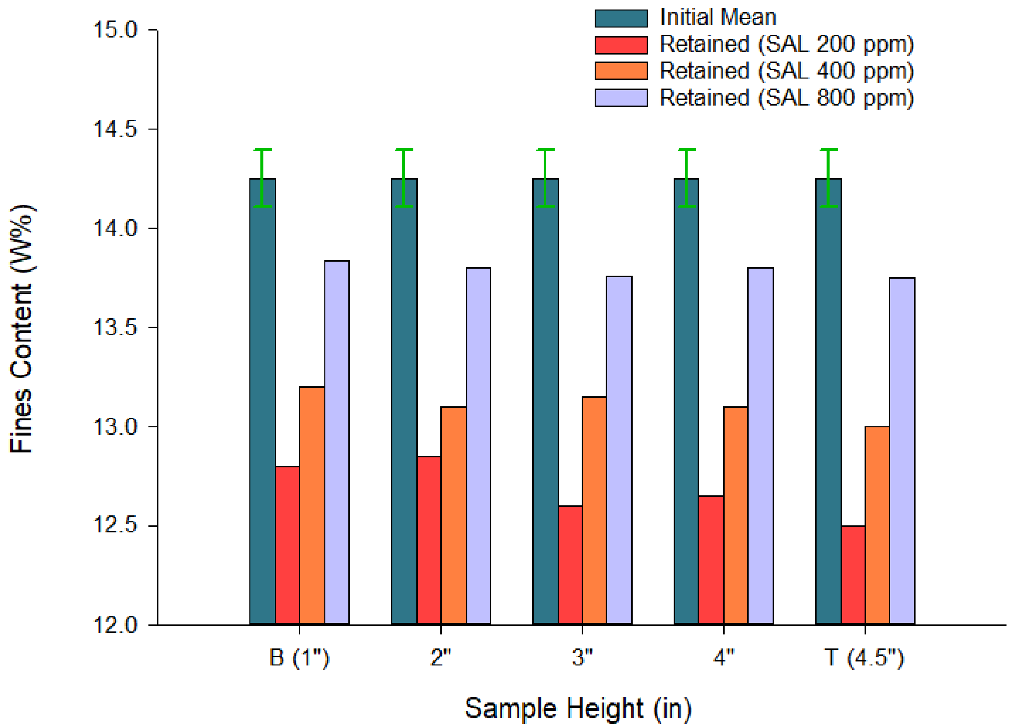

Figure 4.11: Initial and final fines content profile for the test using SL 0.010" and different brine salinity.

4.4 Fines Migration Modeling

This study adopts a coupled mathematical model based on governing equations describing fluid flow, release, transport, and retention of fine particles in porous media. The effect of salinity transport happening only at the first pore volume injection is neglected. The model geometry shown in **Figure 4.12** is the combined cylindrical sand pack and the SL coupon. The model includes three unknown variables, pressure, mobile fines concentration, and retention fines concentration, which are described below.

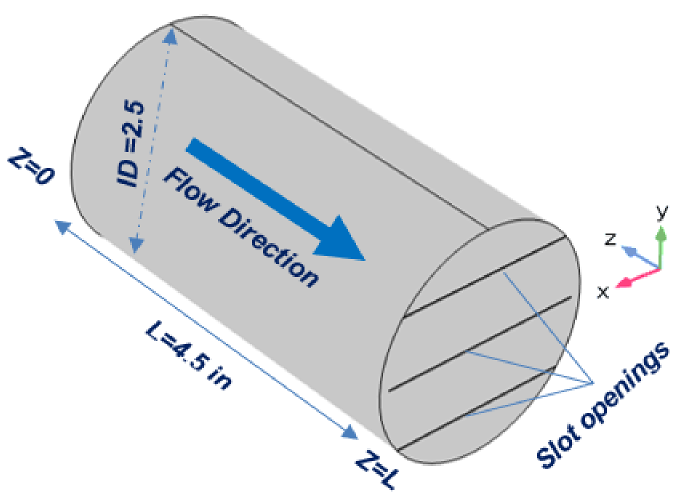

Figure 4.12: The schematic of the numerical model geometry.

4.4.1 Fluid flow

Integrating Darcy's law and mass conservation for single-phase brine yields the partial differential equation (2), known as the diffusivity equation, which is solved for unknown variable pressure (P).

$$U = -\frac{K}{\mu}\nabla P \tag{1}$$

$$\nabla \cdot \left[\frac{K}{\mu}\nabla P\right] = 0 \tag{2}$$

where U is Darcy velocity. Constant brine viscosity (μ) and constant isotropic permeability (k) are used for brine and sand pack that are assumed incompressible for the testing conditions. The initial condition is $P(x, y, z, t = 0) = P_o$. The boundary conditions are constant flow rate (Q) into the inlet area (A), yielding the Neumann condition $-K/\mu\,\nabla P = Q/A$, constant pressure at slot openings as the outlet $P_{out} = cnt.$, and no flow at inter-slot areas and curved surfaces of the geometry walls.

4.4.2 Fine particles flow

The general transport equation for fine particles within porous media is based on the conservation mass of mobile or suspended particles considering convective and diffusive mass fluxes with source (release) and sink (retention) terms [3, 4, 11]. It is assumed that the effect of diffusive fluxes (mechanical dispersion and diffusion) for the relatively homogenous medium is negligible. Therefore, the following equation describes the volumetric mass transport of mobile fines.

$$\frac{\partial(\varphi\, C_m + \sigma_a + \sigma_r)}{\partial t} + \nabla \cdot \left(U_f\, C_m\right) = 0 \tag{3}$$

where C_m is the volumetric concentration of mobile fine particles suspended in the pore volume in terms of volume per unit pore volume, σ_r is the volumetric concentration of retained fine particles at pore throats in terms of volume per unit bulk volume, σ_a is the volumetric concentration of retained or attached fines particles at pore surfaces in terms of volume per unit bulk volume, φ is the instantaneous porosity and U_f is the velocity of fine particles [4]. Prolonged stabilization of pressure drops from experimental observations and pore-scale calculations indicate that particles also move with velocities relatively lower than the fluid flow velocity due to the rolling and sliding of the released particles along the pore surfaces [4]. Therefore, to account for fast and slow particles, the dimensionless parameter α as the ratio of fine particle velocity and fluid velocity has been applied in recent macroscopic modelings [4, 17, 27].

$$U_f = \alpha\, U \tag{4}$$

There are various macroscopic equations for the retention rate of fine particles at pore throats [10]. A simplified expression based on the convective flux of mobile fines $(U_f C_m)$, porosity and a coefficient rate $\lambda\ [1/m]$ is considered.

$$\frac{\partial \sigma_r}{\partial t} = \lambda\, U_f\, C_m\, \varphi \tag{5}$$

As mentioned before, an instantaneous release mechanism is assumed under chemical effect by salinity change. Then, the concentration of the attached fines (σ_a) immediately reaches a critical concentration(σ_{cr}) and the term $\partial\sigma_a/\partial t$ becomes zero. The critical retention concentration can be evaluated from experimental tests. The initial conditions are $C_m(x, y, z, t = 0) = \sigma_{ao} - \sigma_{cr}$ and $\sigma_r(x, y, z, t = 0) = 0$. The inlet boundary condition is $C_m(x, y, z = 0, t) = 0$. The outlet boundary condition is unnecessary as neglecting diffusive fluxes yielded a parabolic differential equation requiring one boundary condition.

4.4.3 Porosity and permeability change equations

The effect of released fines from pore surfaces on porosity and permeability increase is usually neglected. It is assumed that most pressure drops occur at pore throats by retaining fine particles. Thus, the initial porosity φ_o is reduced with instantaneous retention fines concentration at pore throats as follows.

$$\varphi(\sigma_r) = \varphi_o - \sigma_r \tag{6}$$

Several permeability loss equations have been introduced in the literature relating permeability to the porosity or retention fines concentration. They include the modified well-known Kozeny-Carman cubic function, quadratic, and negative power functions with linear and non-linear parameters [1,3,4,28-30]. In this work, the following non-linear permeability loss function [28] with two empirical constants β and n is considered.

$$K(\sigma_r, \beta, n) = \frac{K_o}{(1 + \beta\sigma_r)^n} \quad (7)$$

where K_o is the initial permeability. As it is seen, the system of equations described above includes four empirical constants α , λ, β, and n, which depend on the flow properties and porous medium attributes, such as particle and pore size distribution, surface charges, and zeta-potentials of grains and fine particles [31]. Therefore, the model parameters are assumed constant for a specific porous medium and determined by matching the experimental results.

4.5 Numerical Modeling

The differential equations described above are discretized and solved numerically using the finite element method implemented in Comsol Multiphysics [32]. Quadratic elements and Lagrange shape functions were used to discretize the weak integral form of the differential equations by the Galerkin method. A segregated approach, second-order backward differentiation formula (BDF), time-stepping, and direct Newton solver were used to solve the non-linear system of equations implicitly. A quarter part of the geometry is considered for numerical simulation to save memory and reduce computation time, taking advantage of symmetry. **Figure 4.13a** shows the created mesh, and **Figure 4.13b** magnifies the mesh near a slot of the SL coupon. The mesh consists of hexahedron elements, tetrahedron elements for a 0.2" thin domain near the screen where flow streamlines converge toward the slot openings and quadrilateral elements for the slot openings. Previous CFD simulations confirmed a negligible pressure drop by non-Darcy flow through the slots [33]. Therefore, the slot opening was considered the outlet boundary.

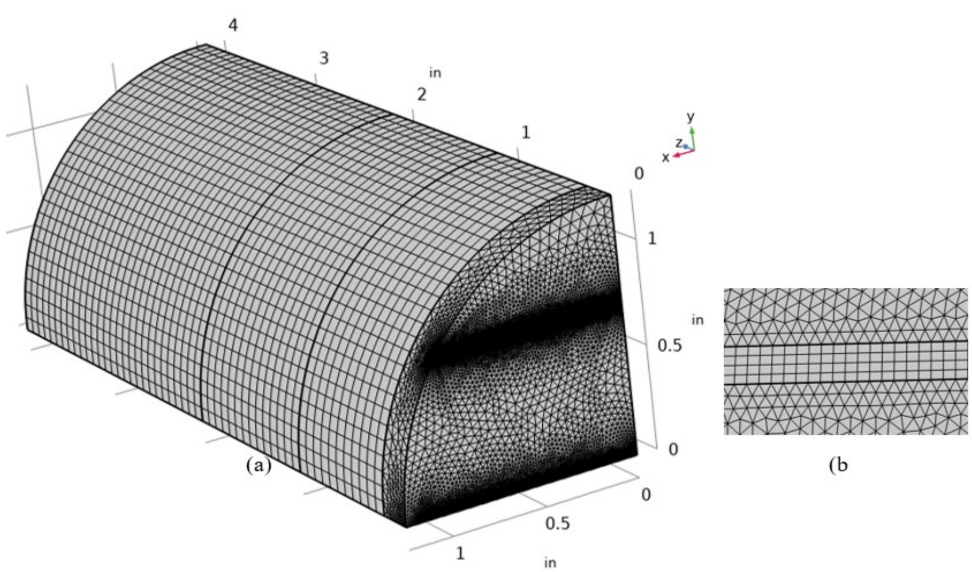

Figure 4.13: Illustration of (a) the mesh used and (b) mesh elements across one screen slot.

A mesh dependency study was performed by progressively refining a base mesh up to six levels. **Table 4.1** shows the maximum element size and number of elements for each mesh.

Table 4. 1: Different mesh specifications for the mesh independence study.

Mesh Parameters	Mesh 1 (Base)	Mesh 2	Mesh 3 (Selected)	Mesh 4	Mesh 5	Mesh 6
Description	Coarse	Normal	Fine	Finer	Extra Fine	Extremely Fine
Max. Element Size (in)	0.179	0.0921	0.0728	0.0508	0.0316	0.0179
Number of Elements	185,883	435,614	565,203	930,376	1,511,183	6,742,459

The integral quantities, including pressure drop of the 2" interval near the screen and the average velocity for the 0.2" domain, as the output parameters of the steady-state flow solution, were considered for mesh convergence evaluation. Plotting these parameter values versus the number of elements in the logarithmic scale, as shown in **Figure 4.14**, reveals that the solution is asymptotically converging from mesh No.3, and results do not change substantially. Therefore, this mesh was considered for the fines migration modeling in this study. Examples of numerical maps of pressure, Darcy's velocity, and retained fines concentration solution near the slots of the sand control screen and the permeability map are shown in Appendix 4A.

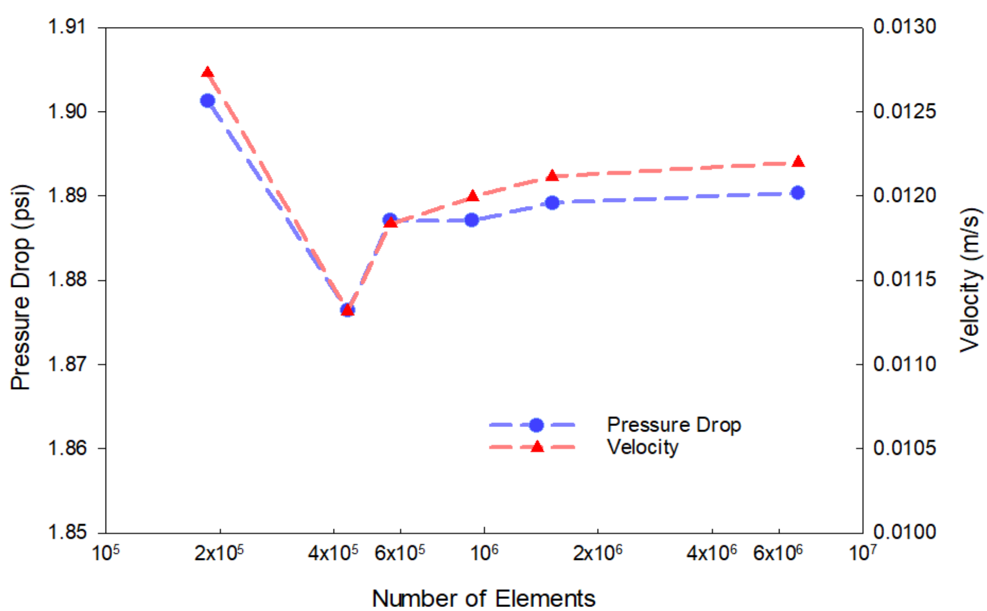

Figure 4. 3: The near-screen pressure drops and local velocities for different numerical mesh.

4.6 Model Results: Calibration and Validation

As established previously [28, 34], the multiple-point pressure method was employed to calibrate or determine the model parameters from two inverse problem solutions found by an optimization technique. Because of the high uncertainty associated with produced fines concentrations measurements, this method considers dimensionless pressure drops for two intervals along the sample incorporated into two objective functions for model calibration. In the sense that the fines migration is a scale-variant process, the pressure drops along a sample interval cannot be transformed to the whole sample just by a length scale. Thus, the non-linear pressure drop curves for two intervals of the sample provide at least four degrees of freedom, resulting in a unique solution for four unknown model parameters in the optimization problem [28]. The calibration can be validated in several ways by predicting dimensionless pressure drops for a different interval, screen, brine salinity, and the general trend of the produced fines concentration for the same sample.

In this study, the experimental dimensionless pressure drops for the whole 4.0" interval and the second 2.0" interval away from the screen are incorporated into the following general least-square objective function for model calibration.

$$Min\ F_{\Delta L}^{\hat{P}}\ (p) = \sum_{t=0}^{t_{end}} \left(\hat{P}(\Delta L, t; p) - \hat{P}_{exp}\ (\Delta L, t)\right)^2 \tag{8}$$

where $\hat{P}$ and $\hat{P}_{exp}$ are dimensionless pressure drops ($\Delta P/\Delta P_o$) from model and experiments, respectively, p is model parameters $(\alpha, \lambda, \beta, n)$, and ΔL is the interval length (4.0", 2.0"). Note, ΔP_o is the pressure drop at the initial time ($t = 0$). The dimensionless pressure drop for the 2-inch interval near the screen predicted from the calibrated model, is used for validation.

This work employed the Levenberg-Marquardt optimizer specifically designed in Comsol Multiphysics software for the least-square objective functions. This optimization technique is a gradient-Newton step-based method that requires the computation of the Jacobian matrix (first derivatives) and Hessian matrix (second derivatives) of a quadratic approximation of the objective function. The gradients were set up to be calculated numerically using a finite difference method rather than an analytical method. It resulted in more accurate results and prevented convergence issues encountered when executing the forward numerical model within iterations. The optimizer minimized the summation of both objective functions to find the optimum solution for the model parameters with an optimality tolerance of 0.001. The main input parameters of the model are shown in **Table 4.2**.

Table 4. 2: Input parameters of the numerical fines migration model.

Parameter	Value
Initial porosity, $\boldsymbol{\varphi_o}$	0.37
Initial permeability, $\boldsymbol{K_o}$ (mD)	2400
Fine particle density, $\boldsymbol{\rho_f}$ (g/cm^3)	2.65
Bulk volume, BV (cm^3)	353
Injection rate, $\boldsymbol{Q}$ (cc/hr)	2000
Initial fines content (w%)	14.25
Initial fines concentration (vol/BV)	0.89775
Initial fines mass (g)	84

The initial permeability assigned for the numerical simulation was determined by solving the steady-state Darcy's flow equation and matching the finalized measured pressure drops for different sample intervals at the first stage. Therefore, an initial permeability of about 2400 mD with some uncertainty was determined before the second flow stage. For example, the difference in finalized pressure drop measured for the intervals using SL 0.018" was about 0.34 psi. However, the simulation (by assigning a permeability of 2400 mD) resulted in a pressure drop difference of 0.22 psi due to flow convergence near the screen. The assigned permeability matched the pressure drop observed for the interval away from the screen. The extra 0.12 psi difference could be due to the small retention of fine particles, especially on the thin sand retention layer at the interface of the sand screen and the sand sample. There are also uncertainties concerning the slight difference in the initial packing quality and the accuracy of pressure transmitters used for both intervals.

The measured and simulated dimensionless pressure drop curves for three different slotted liner screens and three injection salinities, which correspond to the calibrated parameters in **Table 4.3**, are presented in **Figures 15-19**. The results show good agreement for the matched curves and the predicted curves for the near screen interval with a high coefficient of determination, R^2. Calibration values in Table 3, with their 95% confidence intervals, are in the range of typical values reported in the literature [14, 17, 27, 28, 31].

Table 4. 3: Model parameters obtained from calibration for different test settings.

Screen Geometry	Salinity (ppm)	C_{mo} (vol/pv)	α	λ (1/m)	β	n	R^2
SL (0.010 in)	400	0.0213	0.155 (±1E-3)	5.48 (±8E-3)	454 (±2.2)	1.210 (±2E-3)	0.97
SL (0.014 in)	400	0.0213	0.149 (±2E-3)	5.03 (±1E-2)	451 (±1.7)	1.196 (±2E-3)	0.96
SL (0.018 in)	400	0.0213	0.151(±1E-3)	4.99 (±4E-2)	450 (±1.5)	1.198 (±7E-3)	0.98
SL (0.010 in)	800	0.0085	0.117 (±1E-2)	4.38 (±1.5)	130 (±17)	0.758 (±2E-2)	0.98
SL (0.010 in)	200	0.0297	0.20 (±1E-3)	6.0 (±5E-2)	449 (±4)	1.197 (±1E-3)	0.97

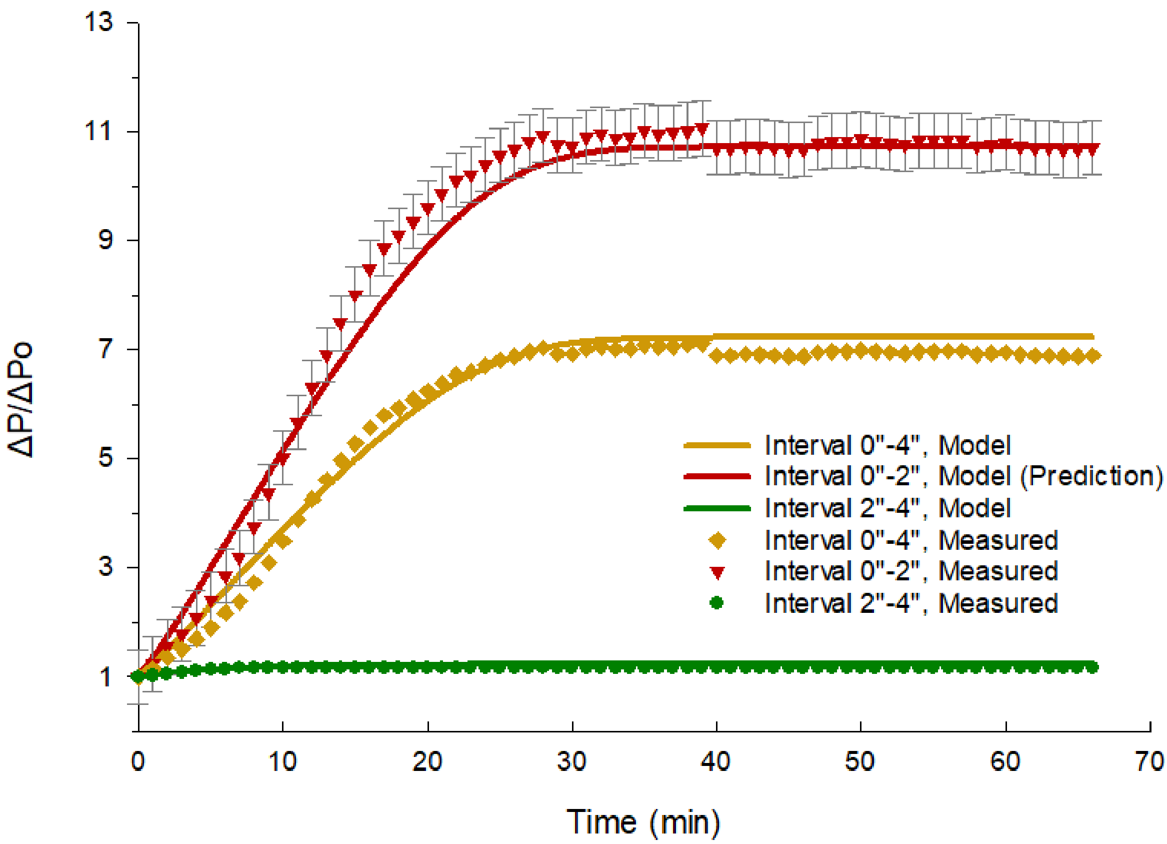

Figure 4. 15: The matched and predicted dimensionless pressure drops with error bars for the test using SL 0.010" and injecting 400 ppm brine.

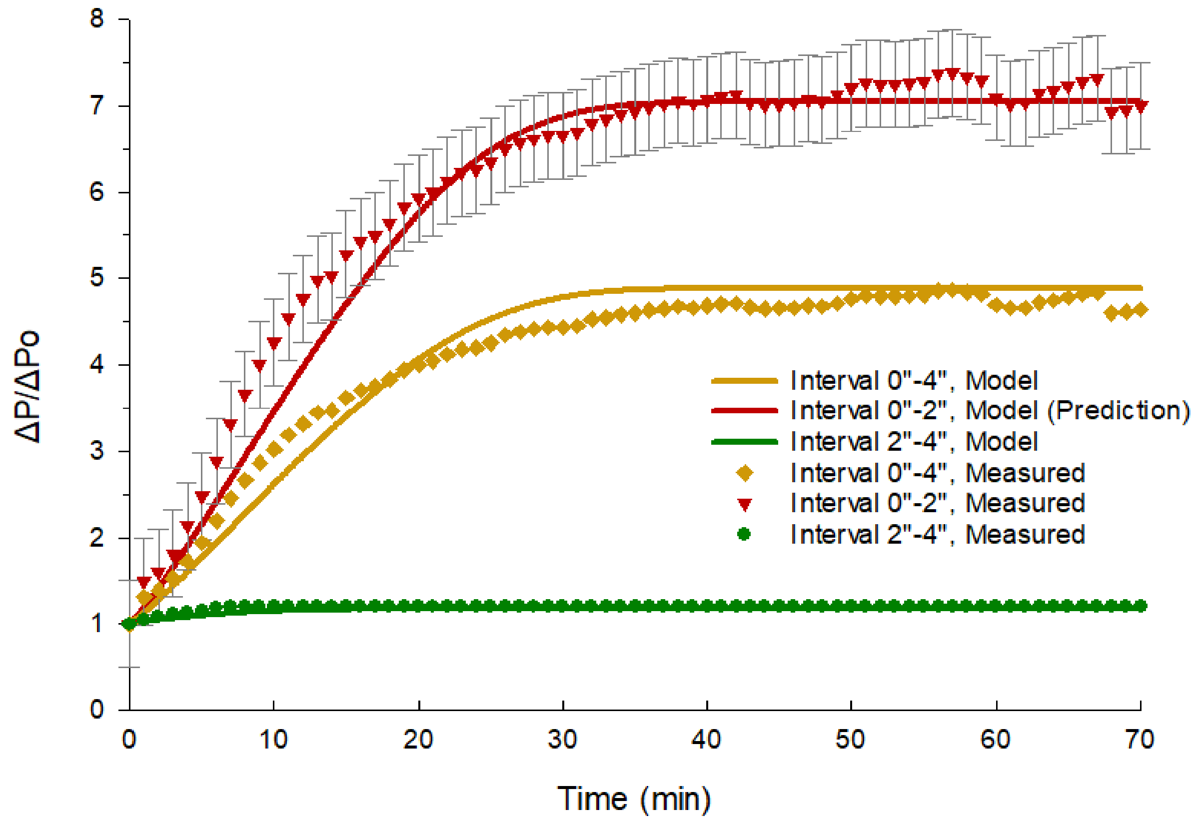

Figure 4. 16: The matched and predicted dimensionless pressure drops with error bars for the test using SL 0.014" and injecting 400 ppm brine.

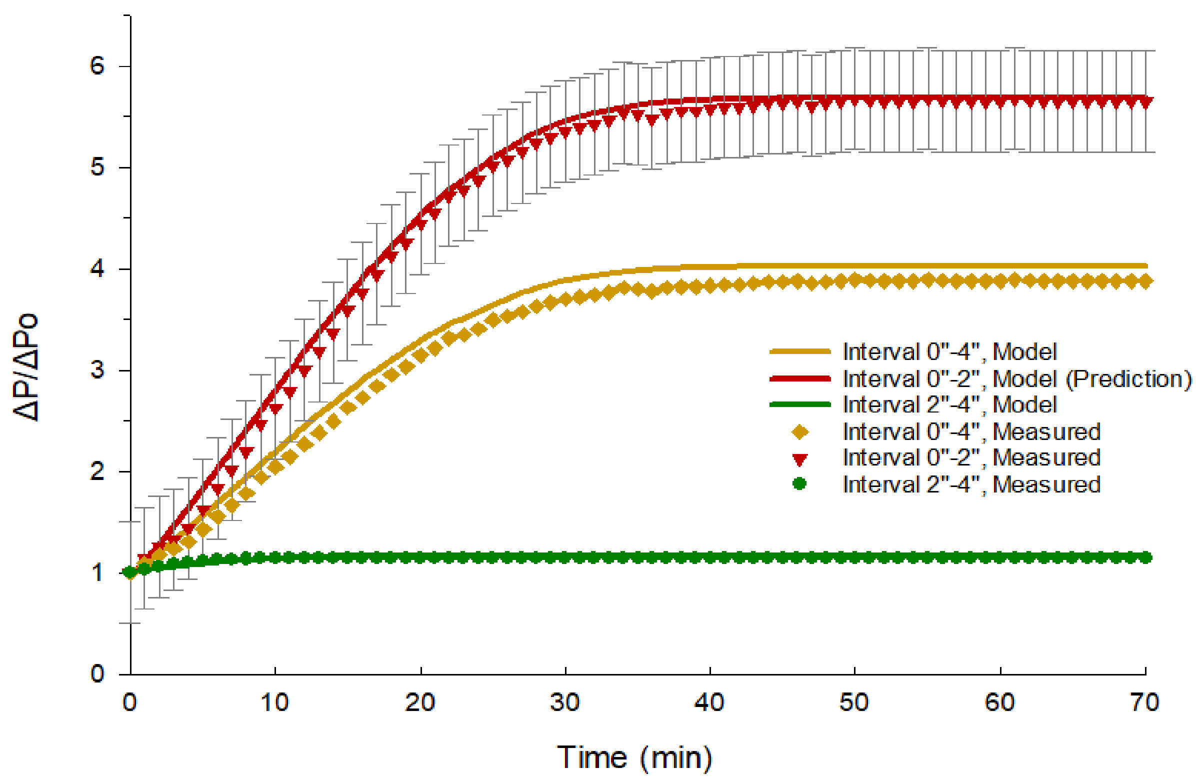

Figure 4. 17: The matched and predicted dimensionless pressure drops with error bars for the test using SL 0.018" and injecting 400 ppm brine.

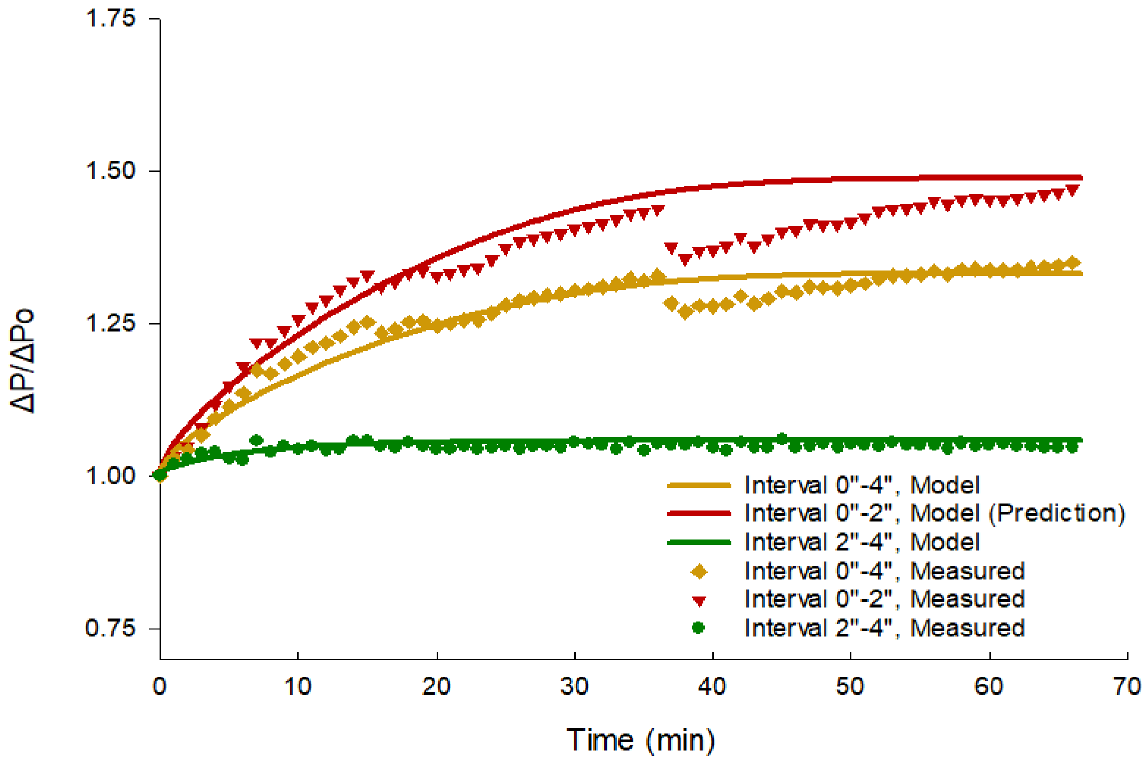

Figure 4. 18: The matched and predicted dimensionless pressure drops for the test using SL 0.010" and injecting 800 ppm brine.

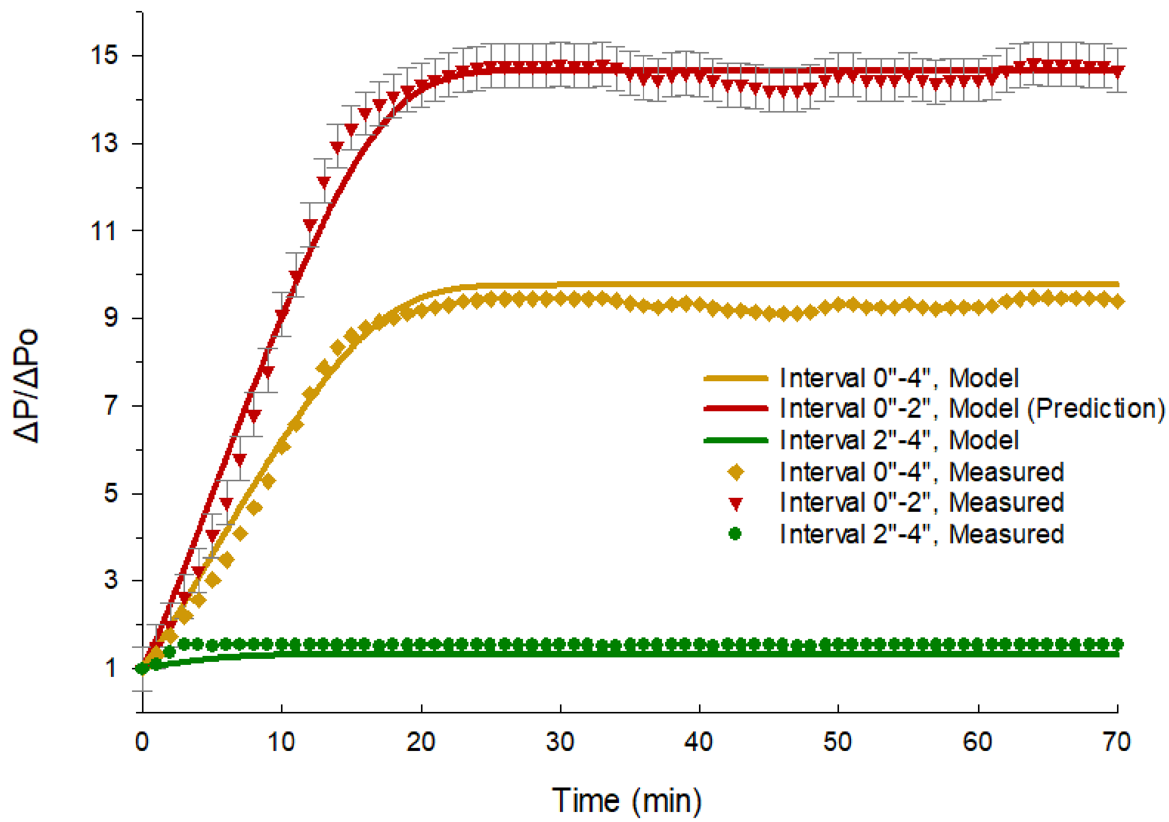

Figure 4. 19: The matched and predicted dimensionless pressure drops with error bars for the test using SL 0.010" and injecting 200 ppm brine.

Some calibrated model results, including instantaneous produced fines concentration, mass conservation of migrating fine particles, and the profile of produced and retained fine particles, are presented in **Figures 4.20- 4.23**.

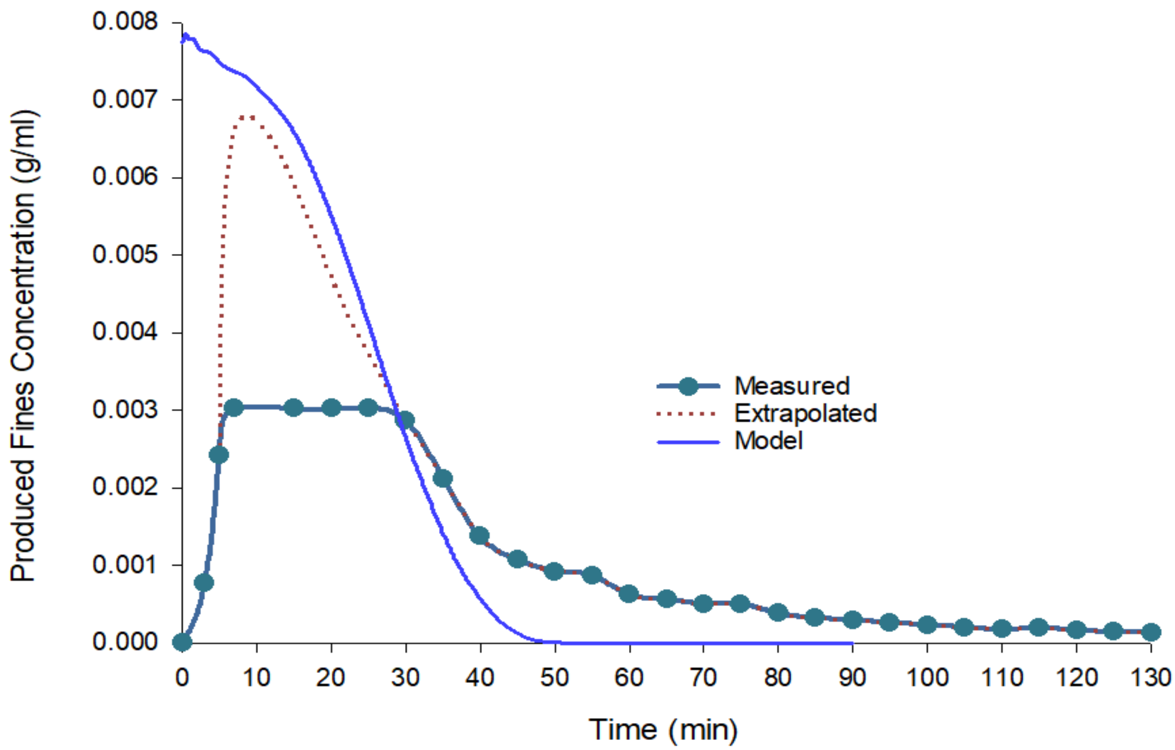

Figure 4. 20: The measured and calculated instant produced fines concentration for the test using SL 0.010" and injecting 400 ppm brine.

Looking at the graph **(Figure 4.20)**, despite the high uncertainty associated with measured produced fines concentration, the model was able to capture the general trend of the measured concentrations. However, it is seen that after 40 minutes, corresponding to 10 pore volume injections, the produced fines concentration becomes zero for the model, while the decreasing trend for the measured values remains for a longer time. This discrepancy is justified later in the discussion section.

The model's mass conservation of fine particles is demonstrated in **Figure 4.21**. The initial mobile fines concentration decreases with time during the fines migration process due to the retention and discharging of the fine particles through the screen. The instantaneous amount of produced and retained fine particles is always equal to the initial mobile fines concentration. **Figure 4.22** shows the instant mobile fines concentration profile along a vertical line from the sample's top to a screen slot opening. A sharp decrease is seen near the screen slot due to the high retention of fine particles near the screen (see **Figure 4.23** for the same line) by flow convergence and inertial retardation.

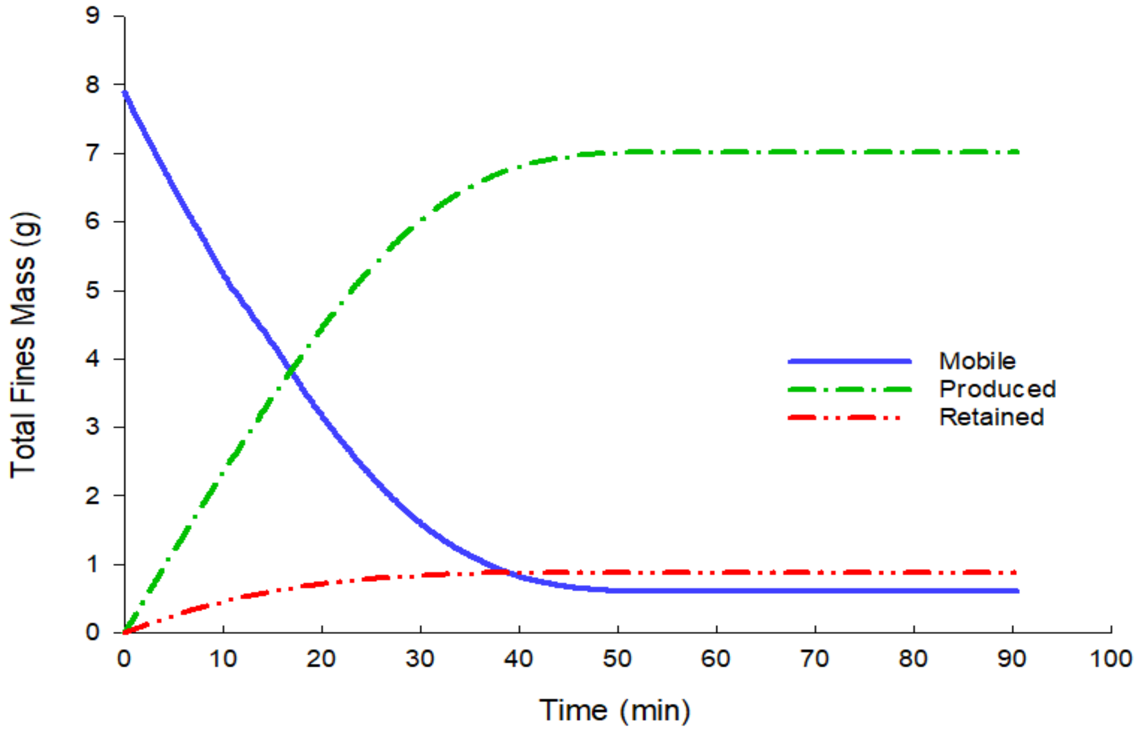

Figure 4. 21: Validity of mass conservation of migrating fine particles by the numerical model.

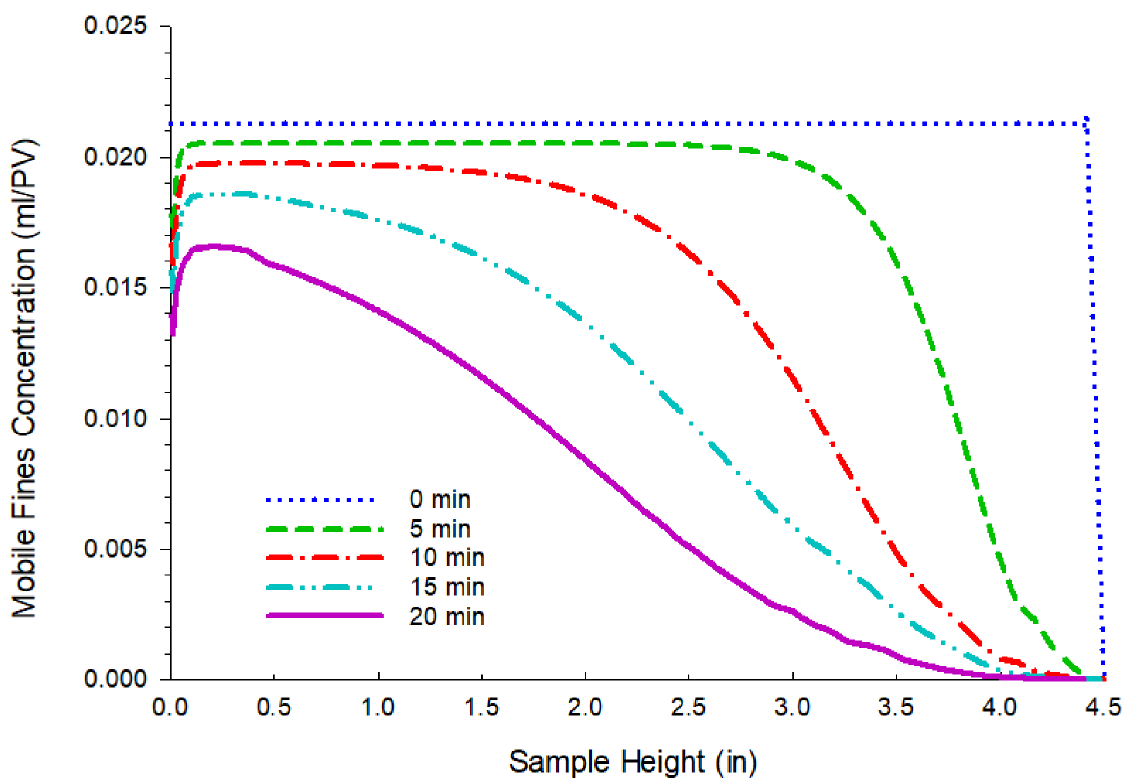

Figure 4. 22: Produced fines concentration profile for the test using SL 0.010" and injecting 400 ppm brine.

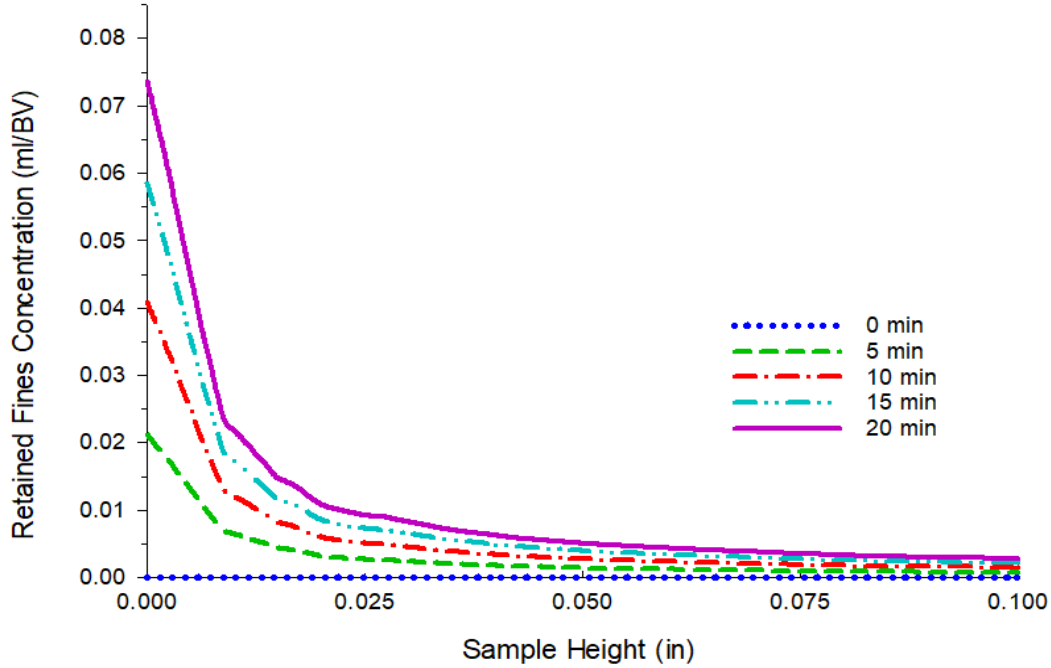

Figure 4. 23: Retained fines concentration profile (near-screen) for the test using SL 0.010", injecting 400 ppm brine.

A parametric sweep study revealed the variation of dimensionless pressure drops with doubling and halving perturbations in four parameters. The results, as shown in **Figure 4.24**, indicate the highest significance of parameter n and others in order of β, λ, and α. **Figure 4.25** shows an increasing trend for the model parameters when the brine salinity is decreased.

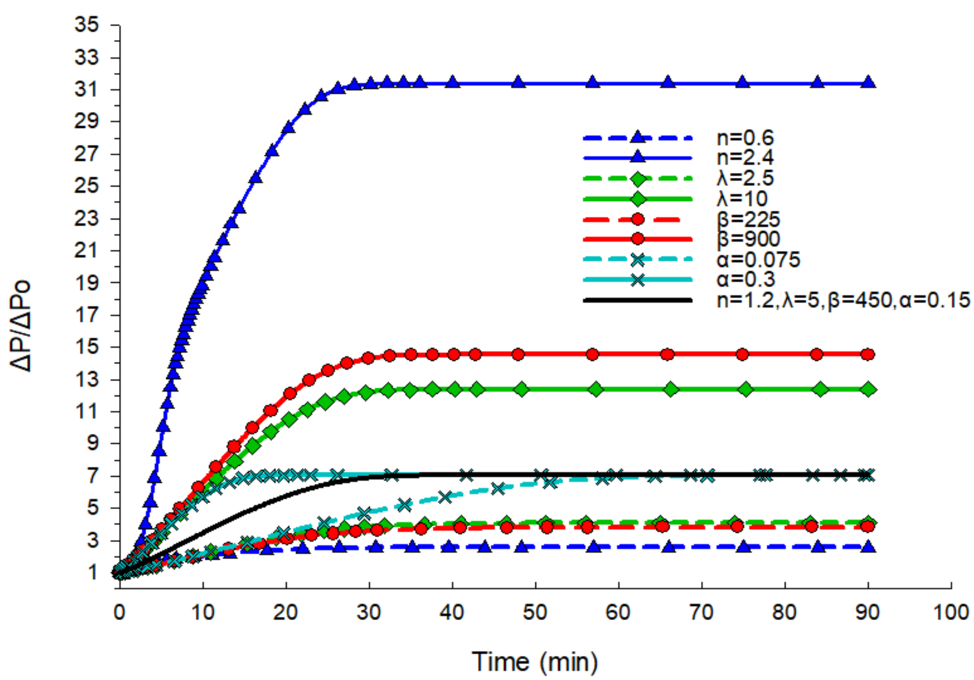

Figure 4. 24: Sensitivity of near-screen dimensionless pressure drop to doubling and halving the model parameters for the base case (solid line), using SL 0.014" and injecting 400 ppm brine.

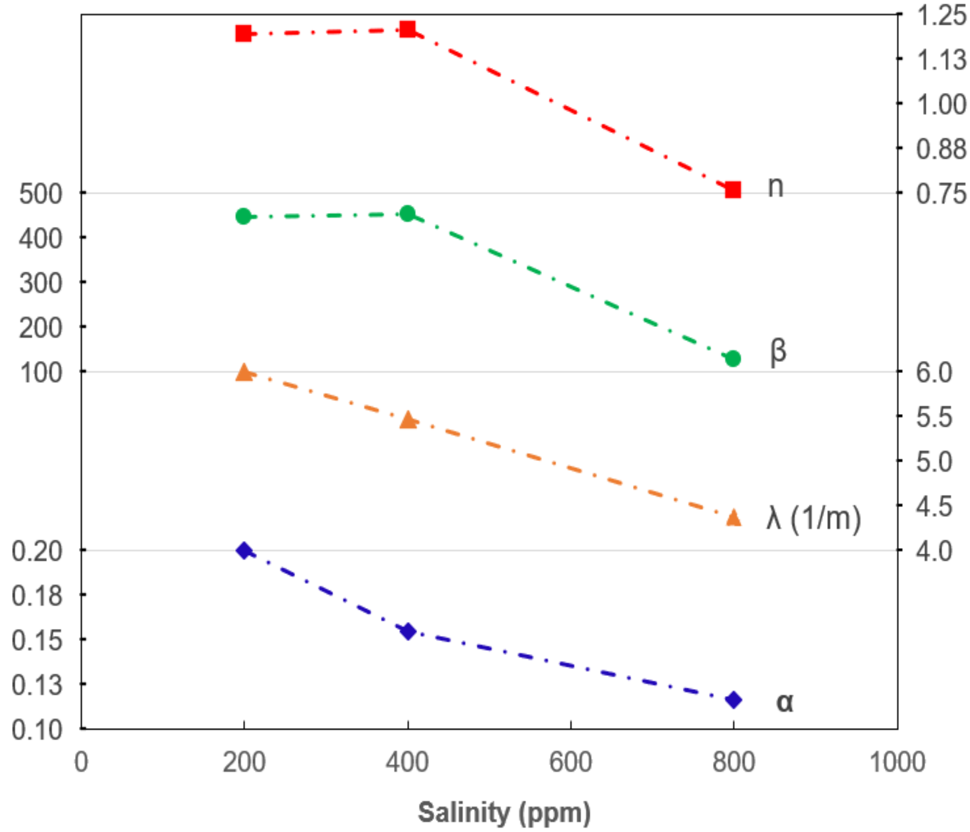

Figure 4. 25: Model parameters variations with brine salinity.

4.7 Discussion

The acceptable agreement between experimental and modeling results revealed that the adopted macroscopic numerical model with the non-linear permeability loss equation could successfully capture the effect of the fines migration process in the sand pack and specifically near the sand screen. The results also verify the primary assumptions of the instant release of fine particles by salinity change and the pore throat retention as the primary mechanism responsible for local permeability impairment. As the numerical simulation confirms, the velocities in the vicinity of the screen, which are two to three orders of magnitude greater than other sections of the sample by flow convergence, result in high retention of fine particles due to the high volumetric flux of mobile particles. Because this effect is local and takes place at the screen vicinity zone, it cannot be evaluated by macroscopic measurements of fines retention along the sample length.

The correlation between model parameters and the porous medium with its permeating fluid has not been explored yet and needs further study. Results obtained here conclude that these parameters are independent of the sand screen. However, the calibration procedure yielded different parameter values for three different flowing salinities. A higher retention parameter (λ) and permeability damage parameter (β) were obtained in lower brine salinities. At lower salinity, the concentration of mobile fine particles is higher, which increases the retention probability. Previous experiments [20] from this continuing research showed insignificantly produced fines concentration under the hydrodynamic effect by applying high flow rates. In this study, the tests were conducted under constant flow velocity representing a high flow rate of one order higher than typical SAGD flow rates, accounting for non-uniform reservoir inflow and severe screen plugging. Therefore, the dependency of the model parameters to flow velocity was not investigated. However, for high interstitial flow velocities much higher than that used in the current tests [27], different α values and constant λ and β values were determined.

Discrepancy observed in **Figure 4.20** is because the numerical model only accounts for the pore throat retention as the primary mechanism for the permeability damage by fines migration. For the same test, it can be seen from **(Figure 4.16)** that the permeability is stabilized after 45 minutes, meaning that the retention rate has become zero. According to the retention rate equation, assuming that the available pore space is not fully clogged, the retention concentration is stabilized when no mobile fines approach the pore throats. In other words, the concentration of the mobile fine becomes zero. However, some bridges at the pore throats may not be stable and break under high differential pressures across the sample and pressure disturbances in the experiment. The concentration of these newly released fine particles is relatively low and takes a long time to produce or retain on previously captured particles. As the experimental results show, the effect of this mechanism on the stabilized permeability is not significant, and the model still would capture the permeability behavior.

Although a detailed look at the uncertainties for the experiment was not taken, a rough total dimensionless error of ±0.495 associated with several sources was assessed, indicating the deviation of calculated dimensionless pressure drops from the measured values. The main contributors to the total error include initial permeability variation along the sample length (inconsistent compaction), the initial stabilized permeability near the screen after the first flow stage (the measurements include pressure drop by flow convergence and non-Darcy flow through the screen), the flow rate fluctuations up to 200 cc/hr affected by discharge pump pressure during fines migration, and lastly the pressure transmitters error of 0.0375 psi. More details about the error assessment are provided in Appendix 4B.

As explained earlier, the initial concentration of mobile particles was evaluated experimentally by measuring the variation of fines content for the top 0.5" interval after completion of the test. The modeling showed large deviations in the results with relatively inaccurate values for the initial mobile fines. Care should therefore be taken in evaluating this parameter. This work determined the quantity of this parameter with high confidence through several primary and repeatability tests. This parameter is usually selected as a matching parameter for the natural core samples with uncertain initial fines content, adding uncertainty to the calibration procedure.

The main outcome of the work is the close agreement between the experimental and modeling results, which validates the capability of the proposed modeling to simulate the permeability damage by fines migration around the sand control screens. The current workflow can be adopted for a laboratory-based sand control design accounting for the fines migration process. An experimentally calibrated model can be used to evaluate several design parameters with less expensive and time-consuming experiments. Also, a laboratory-based prediction of permeability damage at the well-scale modeling, where the geometry of the sand screen is not considered, can be performed based on the calibrated parameters extracted from the numerical model.

4.8 Conclusion

This paper explains the laboratory-based numerical modeling of permeability damage by fines migration in a sand pack restricted by a sand screen coupon emulating the near-wellbore conditions in unconsolidated formations such as oil sands for the SAGD wells. The conducted modeling here accounts for a possible chemical-induced fines migration process around the SAGD wells due to decreasing formation brine salinity by steam condensate. This salinity changes triggers the release of a high concentration of fine particles that would retain more significantly near the sand screen by flow convergence, causing near-wellbore permeability damage.

Beginning with the experimental procedure, the first flow stage with injecting brine salinity identical to saturating salinity resulted in a non-monotonic behavior for the permeability, which was ultimately stabilized at high values (more representative of field values), with insignificant produced fines concentration. This behavior was attributed to the initial low concentration of fine particles accumulated at pore throats that could have been swept under a sufficient flow rate.

For the second flow stage and the tests with different sand screens and flow salinity, the slotted liner screens with a low open flow area yielded considerable pressure drops near the screen compared with wire-wrapped and wire mesh screens. The highest pressure drop observed with the smallest slotted liner screen (0.010 in) was further increased under lower brine salinity of 200 ppm. In all tests, the second 2.0" interval (away from the screen) did not experience significant pressure drops under fines migration, indicating that fine particles could easily pass through the high permeable medium and reach the near screen zone.

The calibrated numerical model could predict the dimensionless pressure drops near the sand screens with minimal deviations from those measured experimentally. Very close values were found for the model parameters in the tests with identical flow conditions and different sand screens, indicating the independence of these parameters to the screen design. However, the tests with different flow salinity of 200 ppm, 400 ppm, and 800 ppm resulted in different values for the model parameters.

The workflow adopted in this study supports the conclusion that a laboratory-based numerical model based on macroscopic governing equations, including release and retention mechanisms of fine particles, could be established and calibrated to simulate reasonably the fines migration process in a sand retention testing setup considered for the sand screen evaluation.

Acknowledgments

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Nomenclature

Latin letters

SRT	*sand retention testing*
SAGD	*steam-assisted gravity drainage*
WWS	*wire-wrapped screen*
SL	*slotted liner*
OFA	*open to flow area*
PSD	*particle size distribution*
SAL	*salinity*
DC-I	*Devon sand class I*
ID	*inner diameter*
ppm	*part per million*
mD	*milli Darcy*
L	*length* (cm)
ΔL	*interval length* (in)
P	*pressure (psi)*
P_o	*initial pore pressure* (psi)
ΔP	*pressure drop* (psi)
ΔP_o	*initial pressure drop* (psi)
∇P	*pressure gradient (psi/cm)*
$\hat{P}$	*dimensionless pressure drop (model)*
$\hat{P}_{exp}$	*dimensionless pressure drop (experiment)*
U	*Darcy's velocity* (cm/s)
K	*permeability* (mD)
K_o	*initial permeability* (mD)
Q	*flow rate* (cc/hr)
A	*cross-section area* (cm^2)
g	*gram*
C_m	*mobile fines concentration* (ml/ml)
C_{mo}	*initial mobile fines concentration* (ml/ml)
U_f	*fine particle velocity* (cm/s)
t	*time*(s)
p	*model parameter vector*
n	*permeability loss function power*

Greek letters

σ_a	*attachment fines concentration* (ml/ml)
σ_r	*retention fines concentration* (ml/ml)
σ_{cr}	*critical attachment concentration* (ml/ml)
σ_{ao}	*initial attachment concentration* (ml/ml)
μ	*viscosity of brine* (cp)
φ	*porosity*
φ_o	*initial porosity*
β	*permeability loss function coefficient*
λ	*retention rate coefficient* (1/cm)
α	*particle and fluid velocity ratio*
ρ_f	*fine particle density* (g/cm^3)

Super/subscripts

o	*initial*
m	*mobile*
r	*retention*
a	*attachment*
f	*fine particle*
cr	*critical*
exp	*experiment*

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Chapter 5: Conclusions, Contributions and Future Research

5.1 Conclusions

Laboratory-based numerical modeling of the fines migration process in a sand retention testing (SRT) set-up was developed for the first time to evaluate the flow performance and permeability loss near sand control screens. The model is based on representative flow and rock properties near the SAGD wellbores in unconsolidated oil sands, focusing on the McMurray formation. A new testing procedure was introduced, accounting for the long-term permeability stabilization and the chemical effect of the fines migration process owning to reservoir formation salinity reduction near the SAGD wellbores. The model calibration parameters were nearly independent of the sand control screen geometric specifications, enabling one to use the numerical model as an alternative to the physical SRT models to minimize costly and time-consuming experiments.

This research was conducted stepwise to investigate the effect of the fines migration process on the flow performance of various sand control screens under hydrodynamic and chemical effects. The conclusions and contributions are summarized as follows:

1. A critical review of the previous studies of the fines migration process revealed that the SRT experiments did not properly account for the fines migration effect. The macroscopic mathematical models did not consider the well completion or the sand control screen interaction.
2. A conceptual workflow was presented to assess the long-term flow performance of the sand control screens under the fines migration process.
3. In contrast to previous sand retention testing procedures, the short-term retained permeability of the sand control screens would not be a reliable flow performance criterion to select the optimum design for formations with considerable fines content. The long-term fines migration process would result in a higher reduction in retained permeability and should be considered.
4. When using the same salinity for the sand pack saturation and brine flow, a non-monotonic permeability behavior was observed with an initial decreasing trend followed by an increasing trend under the fines migration process for the interval near the sand screen.
5. Different test conditions revealed that the release of fine particles near or from pore throats in non-pluggable pathways prevails the effect of straining and plugging of fine particles on thin pore throats at the first stage.
6. The chemical shock effect significantly released fine particles and caused higher pressure drops in the sand packs. A monotonic decrease in permeability was observed under the chemical effect after the first stage of the fines migration caused by the hydrodynamic effect.

7. The permeability behaviors following the previous test procedure at high pore volume injections were not consistent with field and actual core flooding observations in oil sands, more likely due to unavoidable limitations concerning initial attachment of fine particles at pore surfaces, pore size distributions in a synthetic unconsolidated sample, and the amount of mobile fine particles as a function of time.
8. A new test procedure representing worse-case flow conditions for the fines migration in the field resulted in a decreasing permeability behavior due to the high amount of mobilized fine particles and dominant retention mechanism.
9. Reducing brine salinity from a high suturing value (7000 ppm) to deionized water (DI) resulted in significant permeability loss of the whole sand sample due to the high concentration of the released fine particles, masking the flow performance of the sand screen.
10. The fines migration process occurred only when brine salinity was changed from a high saturating value (7000 ppm) to a lower value (e.g., 800 ppm).
11. For the tests with different sand screens and flow salinity, the slotted liner screens with a low open flow area yielded considerable pressure drops near the screen under the fines migration compared with high open flow area screens such as wire-wrapped and wire mesh screens.
12. In all tests, the interval away from the sand screen did not experience a significant pressure drop under fines migration, indicating that fine particles could easily pass through the high permeable medium and reach the near screen zone.
13. A laboratory-based numerical model based on macroscopic governing equations, including release and retention mechanisms of fine particles, could be established and calibrated to simulate reasonably the fines migration process in a sand retention testing setup considered for the sand screen evaluation.
14. The calibrated numerical model could predict the dimensionless pressure drops near the sand screens with minimal deviations from those measured experimentally.
15. Very close values were found for the model parameters in the tests with identical flow conditions and different sand screens, indicating the independence of these parameters to the screen design.
16. Different values were found for the calibration parameters of the numerical model for different flow salinity applied in the experiments, confirming the parameters' dependency on not just porous medium (pore size distribution, porosity) but also fluid properties.

5.2 Contributions and Implementation

5.2.1 Contributions

This research has two major contributions to the experimental and mathematical modeling of the fines migration process around the wells in oil sands under thermal recovery processes such as SAGD. Regarding experiments, a reliable testing procedure that accounts for the fines migration process under the chemical shock effect around the SAGD wells was developed. The low salinity produced water around the wellbore in contact with high salinity formation brine can trigger the release of fine particles and cause significant permeability damage and plugging of sand control devices due to the high concentration of mobile fine particles. Previous sand retention testing works conducted the tests under constant salinity, and the duration of tests was short (maximum two or three pore volume injection), which could not capture the effect of a long-term process such as the fines migration. In the current work, the tests were continued until permeability stabilization so that the flow performance of the sand control screen under the fines migration process could be adequately evaluated.

Regarding mathematical modeling, a macroscopic numerical model accounting for the sand control geometry based on macroscopic rate equations for the release and retention of fine particles at pore throats was developed. The previous modeling works mainly focused on consolidated sands without considering the effect of the near-wellbore completion or the presence of sand control screens. In this research, a 3D numerical model incorporating the geometry of different aperture sizes of the slotted liner screens was constructed and validated against the experimental results.

5.2.2 Implementation

Permeability measurements and several field observations of near-wellbore core samples before and after steam injection in high permeable oil sands under thermal processes such as SAGD have shown that the fines migration process causes plugging of sand control screens and permeability damage. This near-wellbore damage leads to well productivity impairment and increased energy intensity of the thermal process. Therefore, it is essential to develop experimental and modeling techniques as followed in this research to quantify the plugging and optimize the design of the sand control screens in order to minimize the damage and reduce the costly work-over operations.

Currently, the sand control design practices rely on sand retention testing experiments under single or multi-phase flow using commercial sand and fine particles representing the PSD of the considered formation. However, the retained permeability measured in these tests is mainly influenced by the flow convergence and the flow capacity of the sand control screens, where a thin-retention layer of sand quickly stabilizes on the screen. These tests can only evaluate the sand production performance of different sand control screens for the design selection without adequately evaluating the flow performance under a long-term process such as the fines migration.

The proposed testing procedure in this research should be followed to optimize the screen design against the formations susceptible to fines migration. A time-dependent evaluation design based on the proposed testing procedure is required. Because using a narrow aperture design to restrict the sand production within acceptable criteria might sacrifice the flow performance compared with a design where a wider aperture can still restrict the sand production and discharge the migrating fine particles, functioning in the well for a long time. Therefore, for a proper sand control screen selection, the simultaneous sand production performance and the flow performance of the different sand control screens should be evaluated under a consistent testing procedure that is more representative of wellbore conditions.

The release and retention mechanisms of fine particles within the porous media are a complex function of porous media structure (particle and pore size distribution, tortuosity), particle's wettability, particle's electrokinetic properties (zeta potential), and other factors. Therefore, conducting the tests using natural oil sands and fluids would give more realistic results.

Concerning the developed modeling procedure, the numerical model can be used instead of the physical model to evaluate the effect of different parameters such as initial porosity, initial permeability, initial mobile fines concentration, fines content, different sand control screen geometry, and other factors without conducting expensive and time-consuming screening experiments.

The numerical model can also be advanced to the field scale to predict the well productivity under the fines migration process. The laboratory-based calibrated model parameters can be used directly or obtained again by matching the observed available field results.

Another application of the numerical model could be to invetigate a proper skin factor for the well completion string under the fines migration process. The results of different sand control screen geometries and the simple geometry without the sand control screen can be used to develop a correlation for the skin factor.

5.3 Future Research

The workflow followed in this research is generic and can be extended to further research on the fines migration process in SRT experiments under other conditions, including multi-phase flow, high pressure, high temperature, and natural fluids and rock samples. The two-phase flow of melted bitumen and condensate water or high viscous water in oil (W/O) emulsion flow in the SAGD recovery would affect releasing (under high drag force) and dislodging (by pressure disturbances) of fine particles in porous media near the sand screen. A more representative testing procedure could be conducted by introducing steam to a natural oil sand sample in a high-pressure and high-temperature (HP-HT) SRT setup.

The current numerical model considered the slotted liner screen geometry. Other geometries such as wire-wrapped and punched screens can also be adopted.

From a laboratory-based calibrated numerical model, one could determine a skin factor for the contribution of the sand screen to the permeability loss under fines migration by running the model with and without the screen. This skin factor can be incorporated into the well-scale numerical simulations to assess better the significance of the fines migration process on well productivity impairment. In well-scale numerical simulations, the screen geometry is not considered.

The numerical model can also be calibrated and validated by the field measurements of pressure drop under steady-state flow conditions and serves as a prediction tool to assess the time-dependent flow performance of the well under the fines migration process.

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Appendix 4A

Examples of numerical maps of pressure, Darcy's velocity, retained fines concentration solution near the slots of the sand control screen, and the permeability map

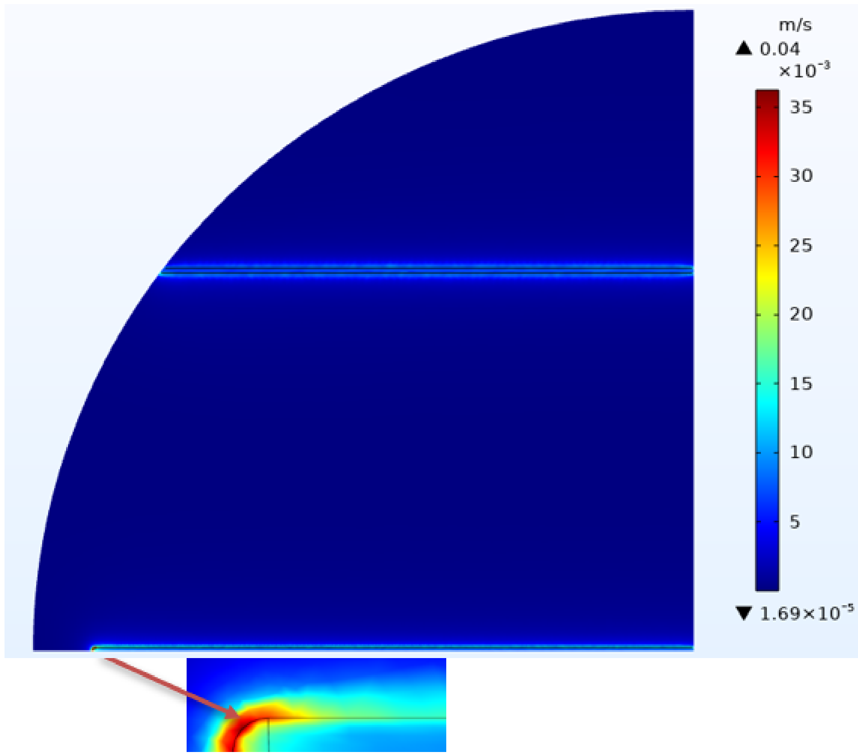

Figure 4A. 1: Darcy's velocity map near the slots, SL 0.010", top view.

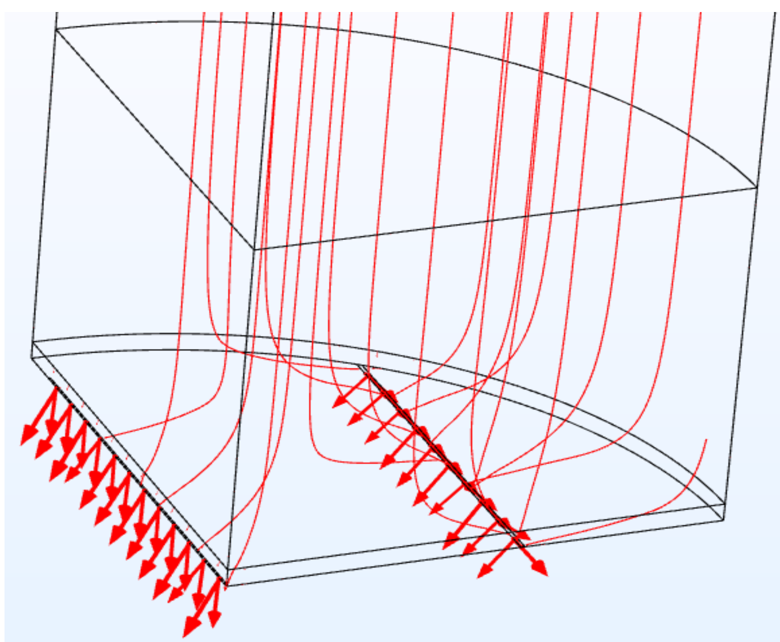

Figure 4A. 2: Flow streamlines, converging toward slot openings.

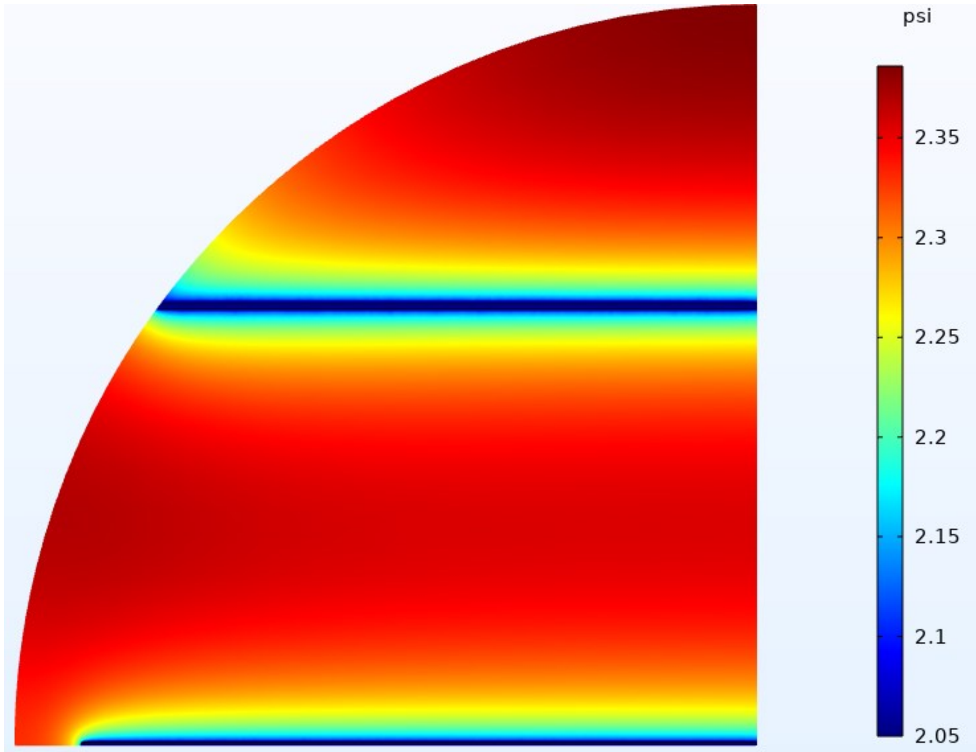

Figure 4A. 3: Pressure map solution near the slots before fines migration process, SL 0.010", 400 ppm brine flow top view.

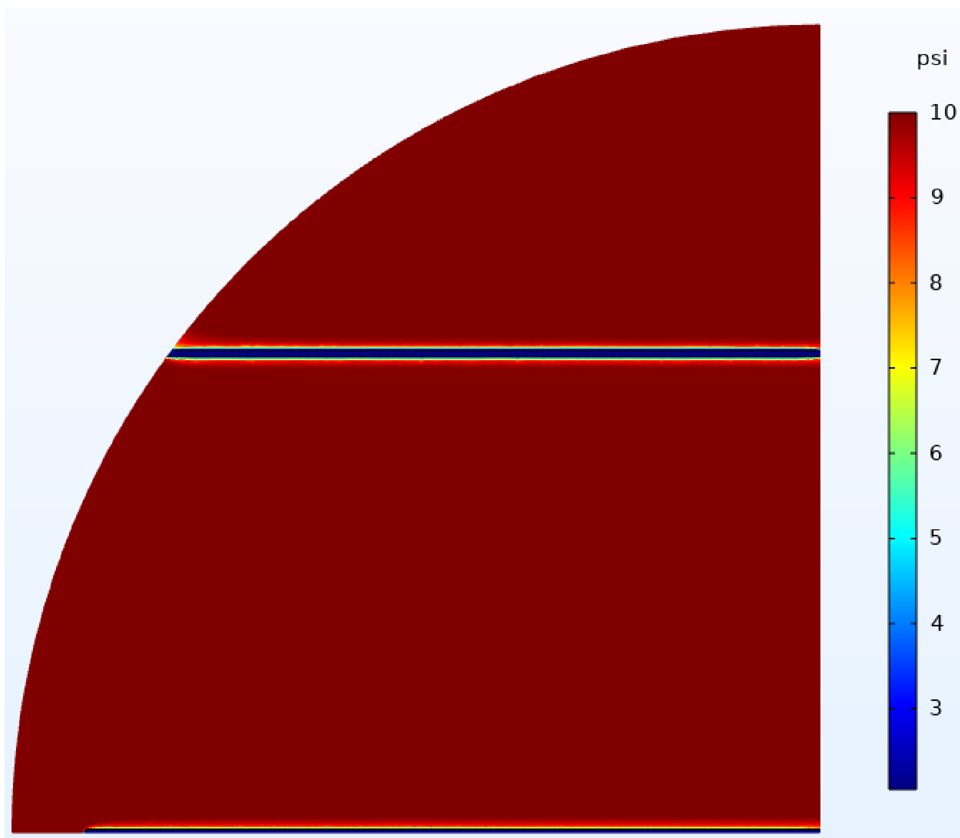

Figure 4A. 4: Pressure map solution near the slots after fines migration process, SL 0.010", 400 ppm brine flow, top view.

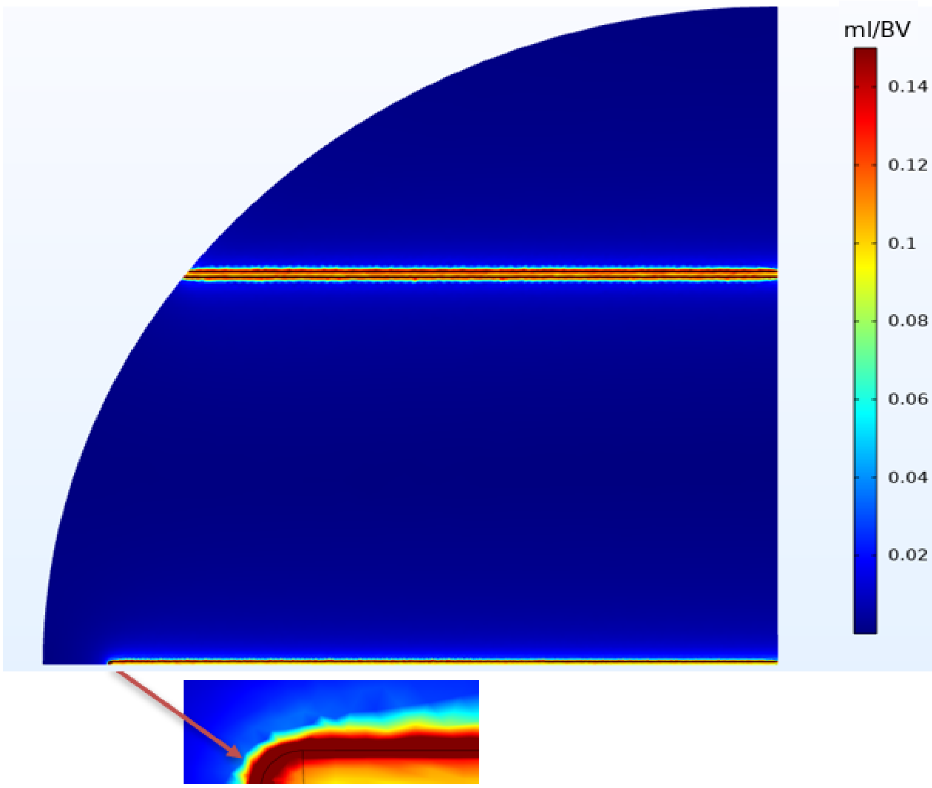

Figure 4A. 5: Retained fines concentration map near the slots after fines migration process, SL 0.010", 400 ppm brine flow, top view.

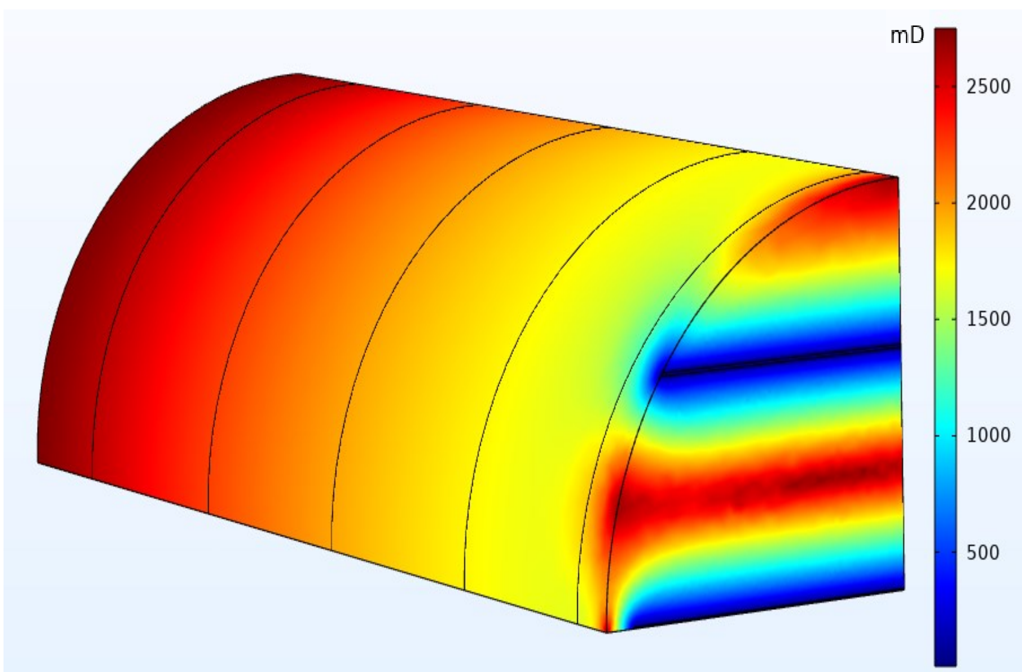

Figure 4A. 6: Permeability map at the end of the fines migration process, SL 0.010", 400 ppm brine flow.

Appendix 4B

Assessment of the experimental uncertainty

1- The initial permeability of the different intervals of the sand pack

The initial permeability measurement of the sample was evaluated at a low flow rate of 450 cc/hr, preventing sample damage by fines migration. Note that the effect of flow convergence near the screen is negligible with this low flow rate. Because of the compaction level, an average permeability difference of about 200 mD for the near-screen and the top interval of the sample, corresponding to a pressure drop of about ±0.3 psi, was observed when all tests were evaluated. This pressure drop difference could affect the calculated stabilized permeability of the near-screen interval after the first flow stage used for modeling fines migration in the second flow stage. As explained in the text, the correct stabilized permeability of the near-screen interval after the first flow stage was determined by excluding pressure drop by the flow convergence through steady-state flow simulation and assuming a single permeability for the model based on pressure drop of the top interval.

2- Pump flow rate fluctuations

The pump used for the tests was a triple head diaphragm pump. All heads at low stroke speed were used to deliver the desired flow rate of 2000 cc/hr with minimum pressure disturbance. However, the pump rate was affected by discharge pressure and flow of fine particles during fines migration. As a result, a flow rate fluctuation from about 1800 cc/hr to 2190 cc/hr was measured during the fines migration process. This flow rate uncertainty could be translated to pressure drops uncertainty of ± 0.07 psi based on calculated permeability from the 2000 cc/hr flow rate.

3- Pressure transmitters uncertainty

The pressure transmitters used in this study could measure the differential pressure along the length of each interval up to 15 psi during the fines migration process. According to manufacturing specifications, they had ± 2.5% accuracy in their span (15 psi), corresponding to ± 0.0375 psi.

According to all the abovementioned uncertainties, a total error of about ± 0.4 psi could be assessed for the pressure drop measurements during the fines migration process. This total uncertainty corresponded to a dimensionless pressure drop of ±0.495.