

An In-Depth Analysis of Fines Migration in Geothermal Reservoirs

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ABSTRACT

Transport of suspensions and colloids through porous media, involving particle capture and plugging, occurs in various geothermal reservoirs and geothermal power plant processes. Fine particle migration is a critical topic impacting production efficiency in geothermal projects, including permeability impairment in the reservoir, plugging surface infrastructure, reducing heat transfer, and causing abrasiveness and erosion in pumps, valves, and production-injection lines. This study presents an in-depth analysis of this problem by examining drive mechanisms, modeling approaches, experimental studies, and field observations.

1. INTRODUCTION

Re-injection of waste brine is essential for sustainable geothermal production and waste brine disposal (Xia et al., 2024). However, reinjection of cold brine can create complex formation-damage mechanisms, potentially reducing injection capacity in porous, unconsolidated formations such as sandstone, schist, conglomerate, and clay-type minerals.

Fine migration has been a critical concern in field practices, impairing well productivity, reducing reinjection, and causing erosion in surface facilities. It occurs especially during turbulent flow in the near-wellbore region, where fluid flow is restricted and velocity increases. Typically, during flow start-up following shut-in, near-wellbore stabilization is disturbed, and fines migrate until a new stabilization is achieved.

Extensive research has examined fines migration and pore clogging in oil and geothermal reservoirs through various experiments such as core flooding, sand-column tests, microfluidic studies, and high-temperature–high-pressure lab investigations (Lever & Dawe, 1984; Hayatdavoudi, 1999; Civan, 2007; You et al., 2013; Mansour et al., 2021). These studies reveal that permeability damage strongly depends on factors like particle size, concentration, flow rate, salinity, temperature, and mineralogy. Additionally, several analytical and numerical models have been developed to explain fines transport, retention, and damage formation. However, many studies are limited to single-scale observations or isolated mechanisms, and combining these findings with field-scale behavior and well performance data remains challenging.

Currently, there is no comprehensive framework connecting fine migration mechanisms, experimental data, modeling approaches, and field evidence in geothermal applications. This study aims to fill that gap by offering an integrated review of fines migration in geothermal reservoirs, including key mechanisms, laboratory and field observations, and advanced modeling techniques. By synthesizing insights across different scales, it aims to enhance the understanding of fines-induced formation damage and to aid in developing better mitigation and reservoir management strategies for sustainable geothermal energy.

2. LITERATURE REVIEW

2.1. Fines Migration Mechanisms and Modeling Approaches

Hayatdavoudi (1999) noted that increasing water cut in oil reservoirs and the presence of water conning or very high production rates cause sand liquefaction, a new term for fines migration. The other important effects were reported as follows: high pore pressure buildup near the wellbore, inadequate cohesive cement between sand grains, and a low angle of internal friction. Having cementing materials such as calcite, dolomite, or siderite at up to 5% or more may reduce sand liquefaction (Hayatdavoudi, 1999).

As we reviewed studies on fines migration in oil and geothermal reservoirs, we found that this process can be categorized into physical, chemical, and hydrodynamic mechanisms that drive fines migration and permeability reduction. The hydrodynamic mechanism describes the effect of high fluid velocity near the wellbore. When the flow rate exceeds the critical rate, hydrodynamic drag forces overcome adhesive forces, allowing fines to become mobile from grain surfaces. As documented in the literature, geothermal reservoirs contain abundant cementing material, but fines migration is dominant due to very high production rates compared to those in oil wells. A typical geothermal well produces between 15,000 and 60,000 bbl/d in western Anatolia, Turkey (Aydin & Merey, 2021). You et al. (2013)

emphasized that, in high-temperature geothermal systems, electrostatic forces acting on fines are weak compared to drag and lifting forces. The migrated particles might be screened at a small pore throat depending on the particle geometry and hydrodynamic conditions.

Geometry and size of pores are as important as fine particles. The mobilized fines are typically small enough to flow with produced fluid through fractured media and pore channels, but they are captured when flow occurs through narrower pore throats or fracture apertures, causing mechanical blockage (Elrahmani and Al-Raoush, 2025). Figure 1 illustrates the suspension and transport of particles within a porous medium at the pore scale. Fluid flow drives particles through constricted pore throats, where variations in pore geometry and local stresses influence particle motion and retention. When the applied hydrodynamic stress exceeds the adhesive forces, particles remain suspended and are transported downstream; otherwise, they may deposit and contribute to pore blockage (You et al., 2013).

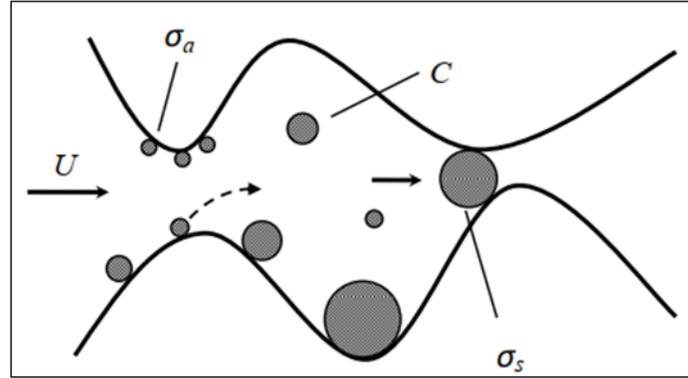


Figure 1: Suspension of transport in the porous media (You et al., 2013)

Electrostatic stabilization is also critical for keeping fine particles attached to grains. As water salinity decreases below the critical salt concentration, electrostatic stabilization weakens. In clay-bearing sandstones, clay particles swell, disperse, and migrate through ion exchange. Fines migration is associated with the presence of kaolinite clay mineral and the fluid flow regime within the wetted perimeter of the pores (Mansour et al, 2021; Khan et al., 2025).

Modeling approaches are conducted to quantify and capture the effects of fines migration on permeability reduction in oil and geothermal wells. Suspension flow of mono-sized particles in cylindrical capillary tubes was studied by You et al. (2013). The proposed model was a physics-based fines migration model for geothermal reservoirs. The model explicitly accounts for transport of suspended fines, fines detachment from grain surfaces, clogging pore throats, and permeability reduction. The model introduced a maximum retention function instead of using the classical detachment law. Finite-difference discretization was applied to estimate time-dependent permeability damage and the spatial distribution of strained fines. The proposed model was validated against field data from a geothermal well in Australia. The study showed that the higher the temperature, the more fines are released, and a higher production rate causes faster impedance growth. Pore-scale modeling may address small-scale flow problems, such as fines migration. Bagrezaie and Dabir (2022) incorporated a pore-scale numerical model and an artificial neural network (ANN) proxy model to estimate pressure drop across a 2D microchannel. The model validation was done against laboratory tests, including suspension injections into the glass micromodels.

Solutions proposed for fines migration can be considered as ways to reduce or prevent it at its source and to mitigate its effects after it has begun. Injecting nanoparticle-assisted surface modification may reduce fines detachment. Mansour (2021) proposed using SiO₂ and MgO nanoparticles agent to stabilize fines at their source. The optimal injection concentration and size of agents were reported to be 0.5 g/l and 30-40 nm for MgO, achieving 64.8% permeability remediation.

2.2. Experimental Studies

In geothermal reservoirs, reinjection is crucial for effective reservoir management; however, the injection of fine particles can clog permeable fractures, compromising both injection and production performance. Xia et.al. (2024) conducted many experiments to optimize tailwater reinjection technology for weakly consolidated geothermal sandstones by using the classical schematic of the core flooding experimental setup in Figure 2. This study investigates reinjection in weakly consolidated sandstone geothermal reservoirs using high-temperature, high-pressure core-flow experiments with a multifactorial design, demonstrating that particle size and flow rate significantly affect permeability damage, while optimized conditions can substantially enhance reinjection performance.

Chai et al. (2022) conducted several experiments to analyze the formation damage of sandstone geothermal reservoirs during decreased salinity water injection. Core flooding, NMR, and contact angle experiments showed that decreased-salinity water injections cause severe formation damage, reducing permeability, shrinking pore throats, and increasing water wettability. SEM, XRD, ICP-OES, and nanoindentation analyses revealed that fine migration, mineral dissolution, and mechanical weakening intensify as salinity decreases. Overall, formation damage is jointly controlled by compaction, fine migration, and mineral dissolution, leading to impaired injectivity and flow in a sandstone geothermal reservoir. According to the study of Zhang et al. (2020), sand-packed core flooding experiments showed that increasing the flow rate triggers the sequential migration of fine and coarse particles. Fine particles are produced, while coarse particles block pore throats, causing permeability fluctuations and overall decline. Higher coarse particle content, temperature, and confining pressure significantly increase blockage risk.

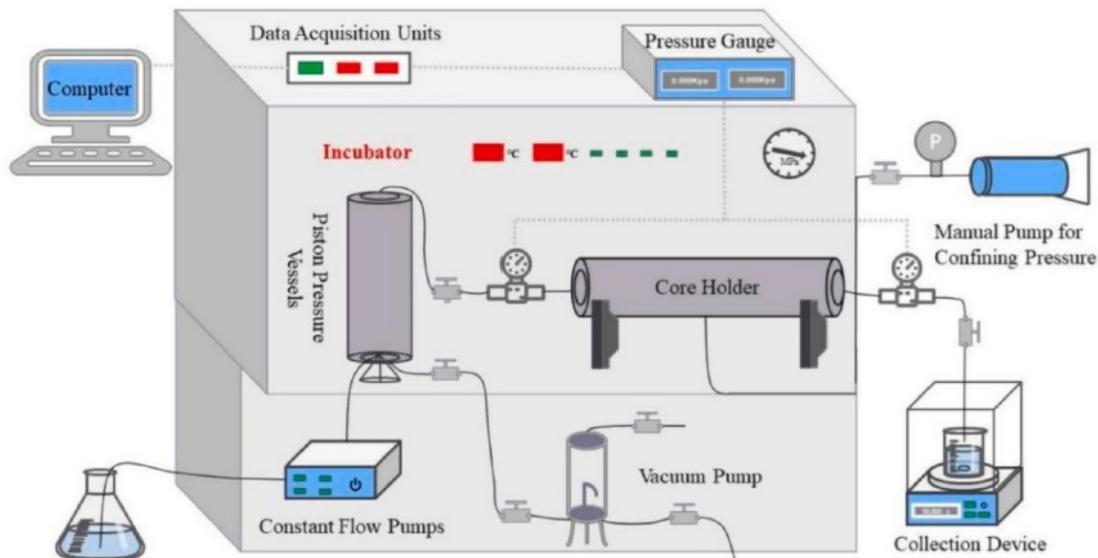


Figure 2: Schematic of the core flooding experimental setup of Xia et al. (2024)

Core flooding experiments combined with 2D/3D imaging showed that internally generated fines strongly depend on sandstone microstructure. Under high flow, poorly sorted pebbly sandstone experienced intense fines migration, clogging, and permeability instability, while well-sorted quartz-rich sandstone remained structurally stable with minimal fines generation (Hao et al., 2025). Similarly, indoor simulation experiments mimicking multi-cycle injection–production in sandstone geothermal reservoirs showed that particle migration, adhesion, and deposition under coupled stress–seepage–erosion cause progressive permeability damage. The damage evolves through four stages—from no blockage to stable blockage—as high-pressure recharge mobilizes fines and disrupts reservoir stress, ultimately reducing injectivity (He et al., 2024).

Laboratory experiments using rock fragments embedded in a composite porous medium were conducted to simulate fines migration under varying flow velocity and salinity. SEM–EDX and DLVO analysis identified fines characteristics and retention conditions. Results showed significant fines migration and retention, and an analytical model successfully predicted permeability damage and well clogging in the Salamander-1 geothermal well in Australia (Badalyan et al., 2014).

Rock property analyses and core flooding experiments showed that the Xining Basin geothermal reservoir in China has low porosity and permeability and is weakly consolidated with high movable particle content. Even at low flow rates, water reinjection caused strong permeability reduction (35–53%), especially with decreasing salinity. Results indicate that near-wellbore particle migration and blockage dominate reinjection capacity decline (Zhao et al., 2021).

Laboratory tests on moderately sorted sandstones (potential geothermal reservoirs in Denmark) showed strong fines production and permeability damage during brine flow. Produced fines included kaolinite, illite, quartz, and detrital minerals, while chlorite and mixed-layer clays remained immobile. Fines generation increased with flow velocity changes, salinity reduction, flow direction reversal, and deionized water injection, causing severe blockage, with greater damage observed in lower-porosity sandstones (Priisholm et al., 1987).

Grifka et al. (2023) investigated that fines migration poses a challenge for reservoir-wide chemical stimulation of geothermal carbonate reservoirs. Flow-through experiments using citric acid on dolostone were conducted under different Damköhler numbers (a dimensionless ratio that compares the rate of chemical reaction to the rate of fluid transport, indicating whether reactions or flow dominate a system) to study dissolution-induced fines generation. Fines were generated in all cases and often reduced permeability; however, at very high Damköhler numbers, large dissolution pathways (wormholes) formed, allowing fines to be transported out or dissolved, so permeability enhancement was maintained (Grifka et al., 2023).

You et al. (2015) proposed a new laboratory method to assess formation damage in geothermal wells. Their coreflood experiments with constant and decreasing ionic strength showed that fines mobilization and straining cause progressive permeability decline. Low-salinity water enhanced clay particle (kaolinite and illite/chlorite) mobilization and formation damage, while permeability stabilized after many pore volumes. Temperature effects indicated that reduced water viscosity dominates, limiting fines detachment and decreasing permeability damage at high temperatures.

Previous experimental studies on geothermal clogging have employed a wide range of laboratory methods, including granular flow tests, sand and soil column experiments, core flooding, and microfluidic models. These studies systematically investigated the influence of particle characteristics, pore geometry, fluid chemistry (such as salinity, pH, ionic strength, and cation valence), flow and thermal conditions, and fluid–rock or fluid–fluid interactions on clogging behavior. Advanced techniques such as confocal microscopy, micro-CT imaging, and high-pressure/high-temperature core flow experiments were also used to capture pore-scale deposition, transport mechanisms, and clogging reversibility under geothermal conditions (Xia et al., 2023).

2.3. Field Studies

Fines migration is a widely recognized cause of permeability decline in porous media, involving particle remobilization, pore-throat clogging, and decline in well productivity or injectivity. During water injection into the hydrocarbon or geothermal reservoirs, particles attached to rock surfaces may detach under fluid shear, clog pore throats, and reduce formation conductivity, especially in poorly cemented reservoirs (Yang et al., 2022). Productivity decline in artesian, geothermal, and oil–gas wells due to natural reservoir fines migration is widely documented in the literature (Kulakov & Berdnikov, 2020).

Fine migration and its associated formation damage can be evaluated and predicted using well testing when pressure, flow rate, and fines concentration in produced or injected fluids are measured simultaneously. Matching these data with analytical or numerical fines-migration models allows calibration of key parameters such as fines retention, detachment, and damage coefficients. Once calibrated, these models enable long-term prediction of injectivity or productivity decline, although their application in routine well testing remains limited. Fall-off and build-up tests, including multi-rate variants, are particularly effective when combined with fines concentration measurements. These tests provide higher sensitivity for detecting fines-related permeability damage, especially in geothermal reservoirs, which are more susceptible to fines mobilisation than conventional oil and gas reservoirs. The resulting model-based interpretation enables reliable forecasting of well impairment due to fines migration and straining. Mechanistically, fines are predominantly mobilized in the near-wellbore region, where high pressure gradients and flow velocities generate sufficient drag and lift forces to detach particles, especially during early production or injection. Skin typically stabilizes once mobilizable fines are produced. Additional fines mobilisation can occur during water breakthrough or injection of incompatible fluids, particularly under reduced salinity or elevated pH, which weakens electrostatic adhesion forces between fines and the rock matrix. Mitigation and remediation strategies include chemical stimulation and fines control treatments. Acidizing can effectively remove fines-induced permeability damage, if fluid–rock compatibility is carefully evaluated; tailored HF-based systems have been shown to dissolve retained fines without inducing secondary damage. Long-term fines management in geothermal wells requires an integrated approach that combines fines dissolution, pore-throat enlargement, and fines immobilisation using stabilisers, polymers, or nanoparticles. These treatments should be designed using DLVO-based interaction modelling and validated through coreflood experiments, together with operational control of flow rate, salinity, pH, and temperature (ARENA, 2015).

As an example, Figure 3 illustrates impedance growth (J in Eq.1), indicating productivity decline during hot water production from the Salamander geothermal field in Australia; the well index decreased by a factor of 2.2 over the production period (Chequer et al., 2021; You et al., 2019).

$$J(t) = \frac{PI_0}{PI(t)} = \frac{q_0 \Delta P(t)}{q(t) \Delta P_0} \quad (1)$$

Where J : impedance; PI : productivity index; q : flow rate; P : pressure; 0 : initial conditions; t : time

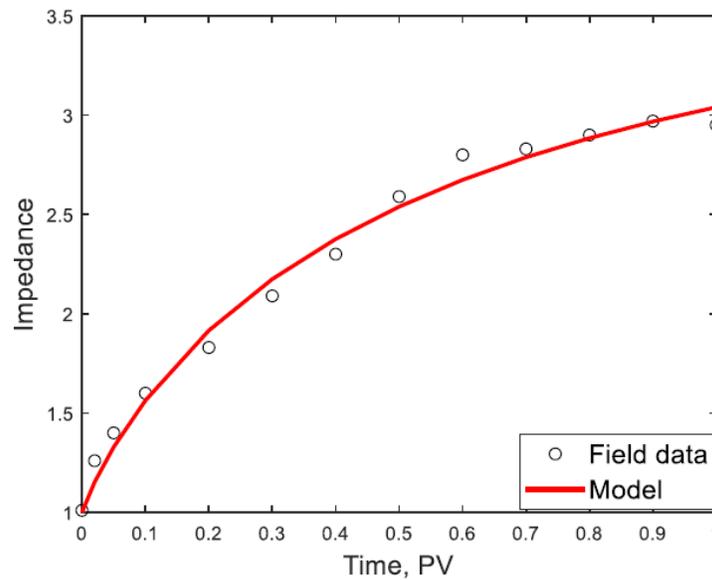


Figure 3: Impedance increase caused by fines migration: Non-linear growth during the developed phase of well exploitation in the Salamander geothermal field (Chequer et al., 2021; You et al., 2019)

According to Chequer et al. (2021), geothermal reservoirs with low salinity water are highly prone to fines migration. Clogging of geothermal reservoirs during tailwater reinjection, leading to injectivity problems in injection wells, is commonly observed. For example, two wells, spaced 1200 m apart west of Paris, were drilled for geothermal operation: one production well with an extraction rate of 130 m³/h and one reinjection well with an injection rate of 120 m³/h. Both wells exhibited a rapid rise in bottomhole pressure and a sharp decline in injectivity over a short period, attributed to clogging of the geothermal reservoir during geothermal tailwater reinjection (Ungemach, 2003). Reinjection clogging is the reduction of reservoir permeability that limits or prevents geothermal tailwater reinjection.

In the porous sandstone geothermal reservoir (PSGR), permeability decline is controlled by fluid hydrodynamics and physicochemical interactions governing clay particles. The main causes include fluid–rock interactions, fluid incompatibility, suspended particle invasion, particle migration, and biological activity (Su et al., 2018). According to the study of Ma et al. (2013), in an ultra-deep PSGR (Lantian–Bahe Formation, Xianyang), physical clogging was identified as the dominant cause of reinjection failure, with particle migration contributing up to 57.5% at 90 °C. The distribution of clogging types in geothermal recharge wells in Figure 4 shows that particle clogging is the most common. Xia et al. (2023) summarized PC effects in sandstone geothermal reservoirs during tail water reinjection as:

- PC is the primary cause of reinjection difficulties in the porous sandstone geothermal reservoir.
- PC is controlled by the coupled effects of particles, fluids, reservoir properties, and reinjection conditions.
- High temperature and low salinity enhance physicochemical repulsion, intensifying clogging by colloidal particles.
- Optimizing reinjection water temperature and salinity can mitigate PC.
- Key challenges remain in cross-scale understanding, multi-field coupling, and clogging prediction.

Briefly, larger particle sizes and higher particle concentrations cause more severe reservoir damage; therefore, multistage filtration should be implemented in surface tailwater treatment to reduce particle size and content (Xia et al., 2023)

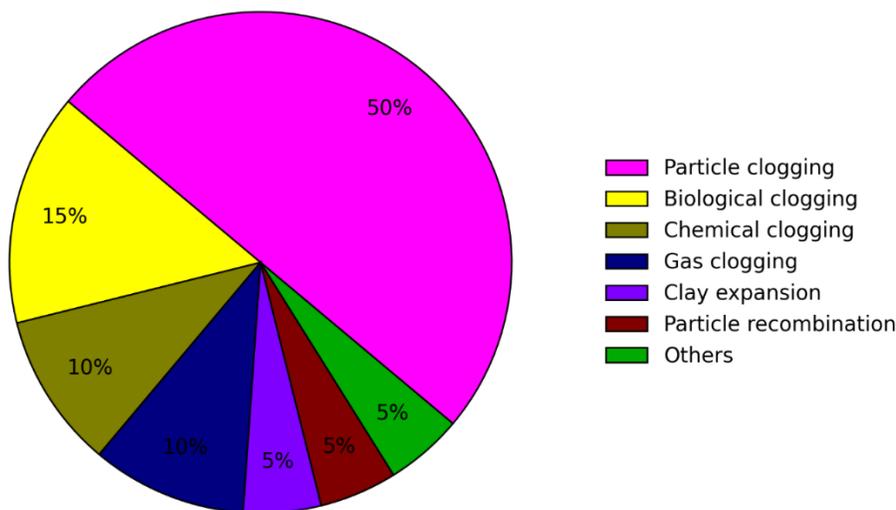


Figure 4: Clogging types in recharge wells (Drawn by using the data from Xia et al. (2023))

Cui et al. (2022) stated that typical sandstone geothermal reservoirs in China are characterized by depths of ~1200–2850 m, temperatures ranging from 58 to 110 °C, porosities of 15–32%, and permeabilities varying from a few millidarcies (mD) to ~500 mD. Formation waters are primarily of the Na⁺–Cl⁻–SO₄²⁻ or HCO₃⁻ type, with TDS values ranging from ~1700 to 7700 mg/L. Water reinjection rates are commonly 20–60 m³/h (open- or closed-loop systems). Across all fields, reservoir blockage during reinjection is widespread and mainly attributed to suspended and reservoir particle retention, chemical reactions, and calcite precipitation, with hydraulic fracturing showing limited improvement in injectivity (Cui et al., 2022). Figure 5 shows how injected water mobilizes fine and clay particles in weakly consolidated geothermal sandstone reservoirs, causing their migration along preferential flow paths. Partial particle retention and accumulation at pore throats lead to blockage, channeling, and reduced permeability during geothermal water reinjection and production, as seen in Figure 5.

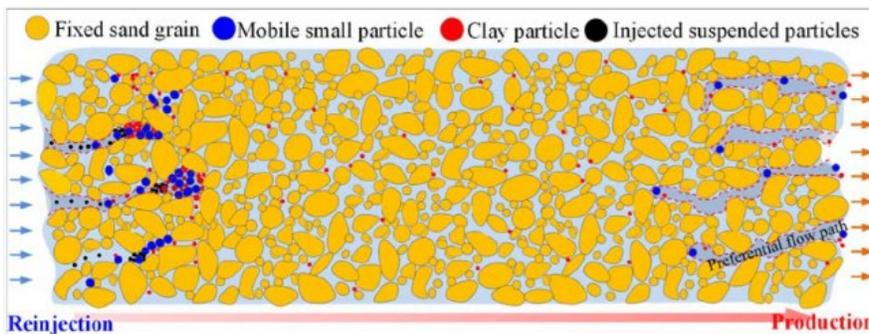


Figure 5: Schematic of particle migration and retention during water-recycling geothermal exploitation in weakly consolidated sandstone reservoirs (Cui et al., 2022)

Field tests in the Szentes geothermal reservoir in Hungary show that near-wellbore particle migration and mechanical clogging are the main causes of injectivity loss. Pump lift improved injectivity, while propped hydraulic fractures were ineffective long-term. Skin-frac

stimulation provided only temporary permeability enhancement, indicating the need for optimized designs and further study (Farkas et al., 2025).

Geothermal energy utilization reduces CO₂ emissions, and reinjection of cooled geothermal water in closed-loop systems helps maintain reservoir pressure and prevent drawdown, subsidence, and thermal pollution. However, in sandstone aquifers, physical and chemical clogging can reduce injectivity, while large volumes of cooled water may cause early thermal breakthrough and lower production efficiency. CO₂ injection can support pressure and enhance injectivity through water–rock interactions, but combined injection of CO₂ and cooled water complicates reservoir cooling and thermal breakthrough behavior (Liu et al., 2020).

In geothermal wells, kaolinite crystals can detach from booklets and quartz surfaces, migrate as fines, and eventually block pore throats, leading to reduced permeability (Holmslykke et al., 2023). According to Nagy and Soboń (2007), permeability decline during injection of unchanged geothermal water is mainly caused by particle release and pore clogging (e.g., feldspar and quartz fines), not by precipitation. High colloidal iron contents can cause severe permeability loss by filter-cake formation, even with fine filtration, depending on particle size, concentration, pore-throat size, and flow rate.

Kottsova et al. (2022) presented a theoretical overview of injectivity problems in geothermal systems supported by a field case in the Netherlands. Field data confirm that flow-path clogging is widespread and mainly driven by biological processes, with no evidence of chemical or physical clogging, highlighting the need for further detailed investigation.

A new mathematical model was proposed by Bedrikovetsky et al. (2012) to analyze formation damage in geothermal wells, using data from the Salamander geothermal field as a case study. The coupled flow–fines migration model shows that well impairment progresses from gradual fines straining to stabilized productivity and agrees well with field observations, predicting more intense fines migration and greater productivity loss at higher reservoir temperatures.

Geothermal wells are completed with 7-inch or 9 5/8-inch slotted liners in the reservoir section. The slotted liners act as the first screen, eliminating large particles (Figure 6).



Figure 6: Screen/slotted liners in geothermal wells (Yang et al., 2018)

Geothermal wells targeting fracture sections are typically drilled an additional 50 to 100 meters to deposit solid particles and drilling debris following flow initiation. As this hole is filled, nitrogen/air lifting is typically used to clean the downhole wellbore. Sand production in geothermal wells might cause erosion of subsurface tubulars (casing, electrical submersible pumps, etc.) and surface infrastructure (separators, pumps, valves, and pipelines). Arikani et al. (2025) presented fines deposition at the surface equipment in the Alaşehir geothermal field, Türkiye (Figure 7).

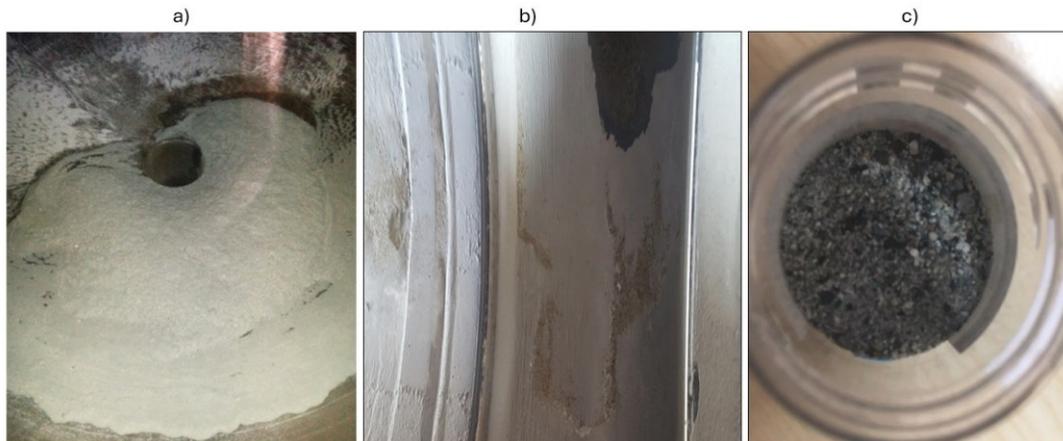


Figure 7: Formation deposition at a) separator, b) valve, and c) drains (Arikani et al., 2025)

The suspended solid particles in the geothermal brine pose a significant challenge for the vaporizer system (heat exchangers). This phenomenon can induce a substantial pressure drop across the vaporizer tubes due to clogging, ultimately reducing the brine flow rate. The analysis of clogging particles within the Alaşehir brine vaporizer revealed a two-fold origin. While a portion originated from the geothermal reservoir formation itself, another component resulted from the mobilization and subsequent accumulation of silicate minerals deposited within the re-injection line situated between the LP separator and the brine injection pumps (BIPs). These mobilized silicate minerals ultimately accumulated at the inlet of the brine vaporizer (Figure 8). To eliminate suspended solids from the geothermal brine, a screener with a 100-mesh size was placed before the vaporizer inlet (Figure 8). It was found that particles accumulated in the screener in a very short time, less than 6 hours. Then, the mesh size was increased to 200 to trap relatively higher particle sizes (Figure 9).

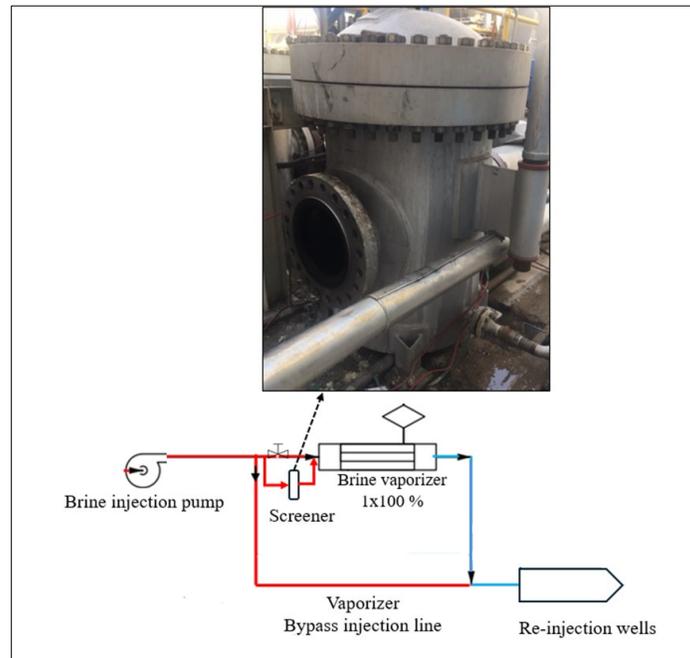


Figure 8: A screener for filtering geothermal brine in the Alaşehir power plant

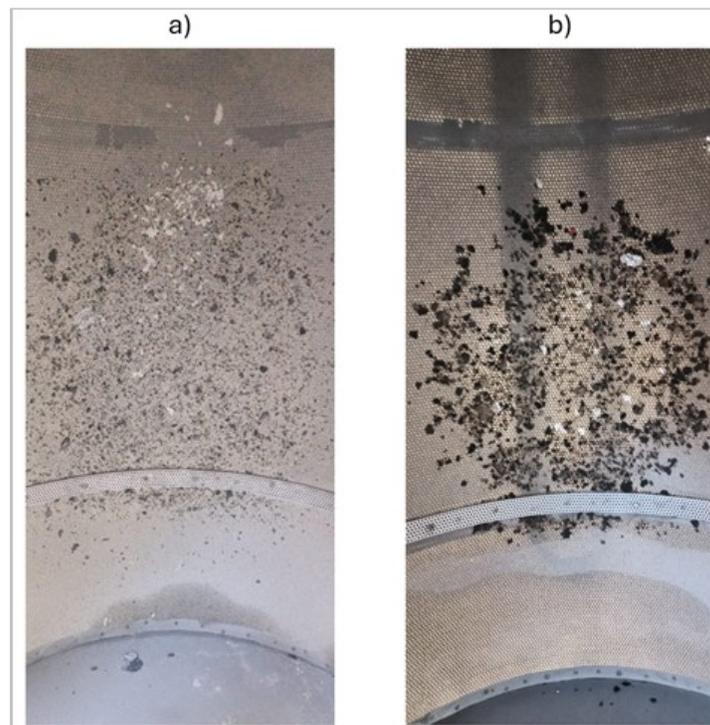


Figure 9: A screener for filtering particles before the brine vaporizer a) 100 mesh size b) 200 mesh size.

Besides, the study emphasized that, due to erosion, the caliper log indicated an enlargement of the inner diameter of the 9 5/8-inch casing from 8.59 inches to a maximum of 8.91 inches in geothermal wellbores in the Kızıldere field, Türkiye (Figure 10).

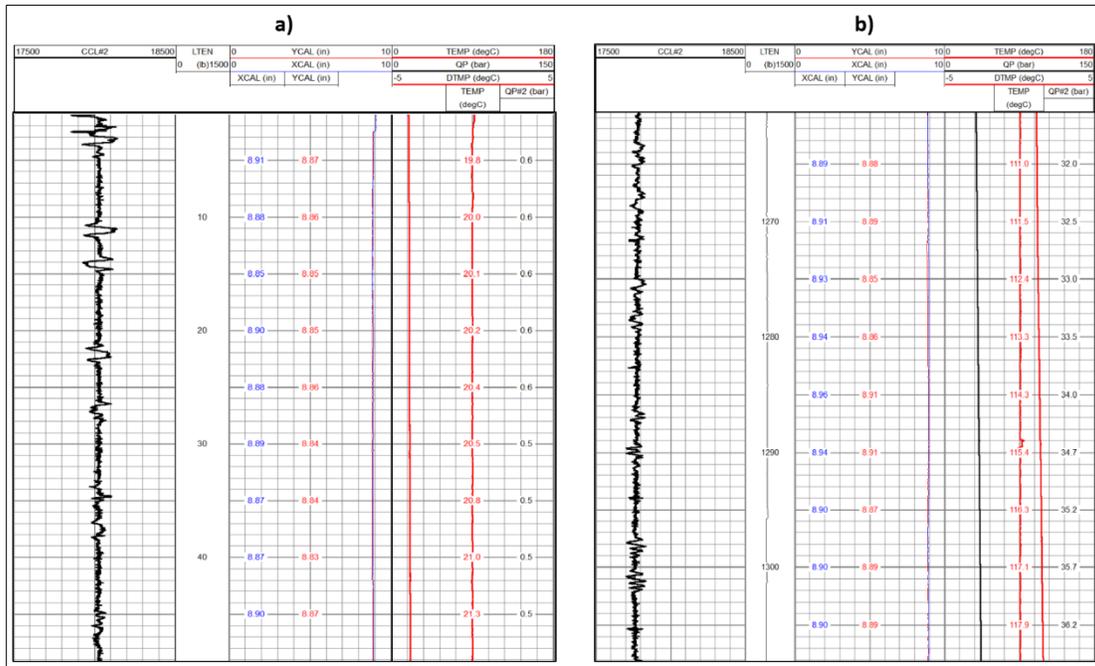


Figure 10: Caliper log measurement in a geothermal well in the Kızıldere field, Türkiye (Arikan et al., 2025)

3. DISCUSSIONS

Different experimental setups, simulations, and field observations show that fines migration and deposition are a near-wellbore phenomenon governed by mechanisms including physical, chemical, and hydrodynamic conditions.

Geothermal systems are different from oil reservoirs, so studies conducted for oil reservoirs need to be revisited to account for high flow rates and temperatures, which we believe have significant effects on fines migration mechanisms. Besides, geothermal reservoirs are generally found in tectonically active regions where natural fractures are developed, so new studies are needed to focus on fines migration in fracture media rather than in porous media. Fines migration in Enhanced Geothermal System (EGS) projects remains a gap in the literature. Therefore, it is an important subject to study not only for proppant backflow but also for formation migration.

Current models still struggle with field-scale simulations because of model assumptions and oversimplified particles and pore geometry. Additionally, it is difficult to determine the aggregate effects of millions of particles flowing in field-scale fines migration. Machine-learning-based studies have been used to reduce computational time and cost. However, a physics-based description is still lacking. Hybrid approaches combining physics-based, laboratory calibration, and data-driven proxies would be a solution to overcome this problem.

Some nanomaterials and microfluids can alter the surface properties of grains and fines to stabilize them and prevent formation and production; however, they are mostly at the laboratory scale, and the economic feasibility of large-scale applications is questionable.

Pressure transient tests, such as buildup, drawdown, and injection fall-off tests, could be used to quantify fines-migration-related skin factor near the wellbore.

Slotted liner design should be carefully done, not only considering particle sizes but also the casing's strength to withstand collapse pressure. This is an important point for well integrity.

The effects of fines migration should be evaluated across all geothermal projects, starting at the near-wellbore region of production wells, extending through casings, wellhead equipment, separators, pumps, production lines, injection lines, and reinjection wells. In this way, production optimization to reduce fines migration would be more comprehensive from the operators' perspective.

4. CONCLUSIONS

This study provides a brief literature review of fines migration in geothermal reservoirs, including fundamental mechanisms, field observations, laboratory experiments, and modeling approaches. The study focuses primarily on near-wellbore problems, but it also addresses tubular and pump erosion.

In contrast to oil reservoirs, in geothermal wells, high flow velocity and temperature conditions weaken the electrostatic stabilization of fines. However, as in oil reservoirs, the particle geometry and size are important for fines migration.

Hybrid modeling approaches were found to be the most appropriate methods for addressing modeling issues in field-scale simulation of fines migration.

Critical research gaps in fines migration in geothermal reservoirs include studies of fines migration in fractured reservoirs, EGS, coupled thermo-hydro-mechanical effects, and field-scale validation and feasibility studies for mitigation solutions such as chemical stabilizers and nanoparticles.

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