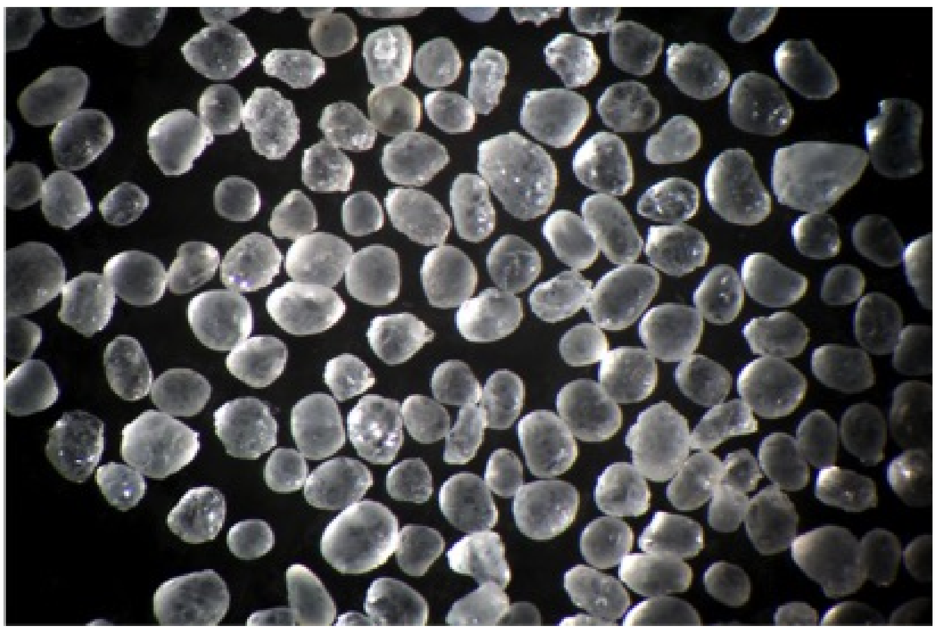
EPSRC Centre for Doctoral Training in Industrially Focused Mathematical Modelling



Pore Blocking by Clay Fines

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1. Introduction

1. Background information

> Low salinity water flooding is of particular interest, as the reduction of salinity encourages the release of fines.

During the process of oil extraction, fluid (often water but can also be gas) is injected into the reservoir in order to maintain pressure, ensuring that oil continues to flow out of the wells. It is also done to ensure that gas trapped in the oil is not released whilst it is travelling up the well, which can damage the piping. Further, it is also common to change the fluid in some way in order to encourage more oil to be released. Such methods are collectively referred to as “Enhanced Oil Recovery” (EOR). One such method is “low salinity water flooding” in which the salinity of the water injected into the reservoir is reduced, and the ratios of different salts are changed. BP have seen that this method can have the unfortunate side affect of releasing small particulates, referred to as “fines”, into the reservoir. These fines sometimes reduce the permeability of the rock in which the oil flows.

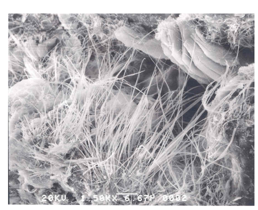
> We need to consider three problems: fine generation, migration, and deposition.

The transport of fines in an oil reservoir is split into three processes: fines generation, fines migration, and fines deposition. Fines generation refers to the processes that cause fines to be released from the rock, fines migration refers to how fines move throughout the porespace, and fines deposition describes how fines are deposited back onto the rock. It is the deposition of fines that causes loss of permeability, although it is, of course, important to understand the two other processes as these define how and where the fines reach the point where they are eventually deposited.

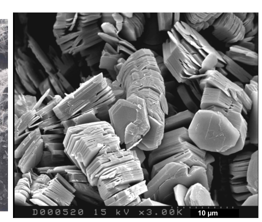
In a reservoir, rock grains are often coated with a layer of small particles of clay and silica. These particles can be released through a combination of chemical changes and hydrodynamic forces. Small particulates may also be introduced in the injection fluid. Therefore we have two process for fines generation, externally introduced fines and internally generated fines.

Fines are transported as a suspension through the porespace by fluid flow, and interact with each other by colliding. An important question relevant to the migration of fines is the stability of the suspension. A suspension of particulates is called stable if these particles stay separate and do not coagulate, and is called unstable otherwise.

Each type of fine has a different size and shape and is distributed differently within the rock. In figure 1, we show close up images of the four main types of fines encountered in oil reservoirs, namely Illite, Kaolinite, Chlorite, and Silica.

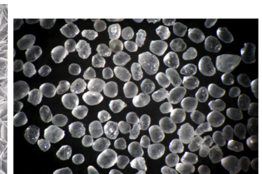


(a) Illite Fines



(b) Kaolinite Fines

(c) Chlorite Fines



(d) Silica Fines

Figure 1 – Images of the different types of fines.

Our aim in this project is to build a mathematical model to describe the motion of fines within a porous structure.

2. Model for Migration of Fines

We consider three important processes: fines generation, fines migration, and fines deposition.

First, we develop a model for fines migration and deposition. Our model consists of two components: fluid flow and fines motion. We use "Stokes flow" to model the fluid flow and a "particle model" (where we model our fines as point particles) for the motion of the fines.

We assume for simplicity that the pores are square and the throats joining pores are rectangular, as shown in figure 2. We assume that the pore has length L ($\sim$ 100 microns) the two pore throats have heights H_1 and H_2 from the base of the pore respectively, and have diameter D_1 and D_2 respectively.

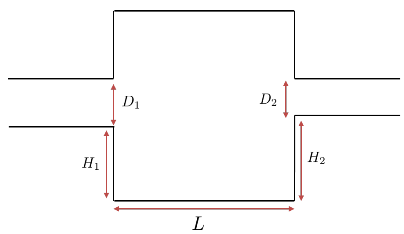


Figure 2 – Pore Geometry

We will make the following simplifying assumptions:

1) inertia of the fluid can be neglected,

2) the fines do not affect the flow,

3) the fines are small,

4) the fines are smooth, spherical and do not deform,

5) the only forces acting on the fines are drag, gravity, and buoyancy,

6) the fines experience "Stokes drag" (the drag is proportional to the difference in the velocity of the fine and the fluid),

7) the fines may collide, but otherwise do not interact,

8) the fines stick to the walls of the pore on contact,

9) new fines are not generated at the walls or in the flow,

10) the fines are released from random positions inside the left-hand throat .

We note that we will consider a wide range of possible velocities and, at the extreme fast end, it is possible that some of these assumptions begin to break down. It is worth noting that the assumption that the fines stick to the wall on contact is very simplistic since, in reality, the fines stick to the wall due to electrostatic interactions. Whether or not the fine sticks will depend on a force balance between this electrostatic interaction and the drag force due to the fluid.

Our modelling assumptions make calculating the trajectories of the fines much less computationally expensive.

Since we assume that the fines do not affect the flow, one advantage of our model is that we are able to calculate the fluid flow in the pore, and then subsequently solve for the trajectories of the fines, which makes the computations relatively easy.

In section 3 we will vary the diameters and position of the throats and the size of the fines, in order to compare how these attributes affect the trajectories of the fines.

In order to consider how fines are generated in a reservoir. We build a simple model for the release of an individual fines particle, assuming that it is a smooth sphere pinned to a wall of the pore by a small asperity, as shown in 3. We have six forces acting on the fine, gravity $\mathbf{F}_g$, the drag force $\mathbf{F}_d$, the normal force at the normal force at the wall $\mathbf{N}_1$, the frictional force at the wall $\mathbf{F}_1$, the normal force at the asperity $\mathbf{N}_2$, and the frictional force at the asperity $\mathbf{F}_2$.

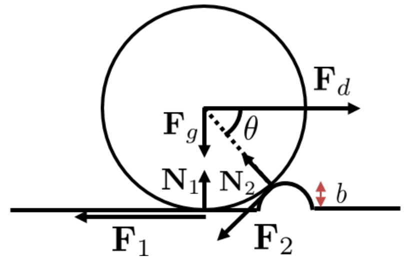
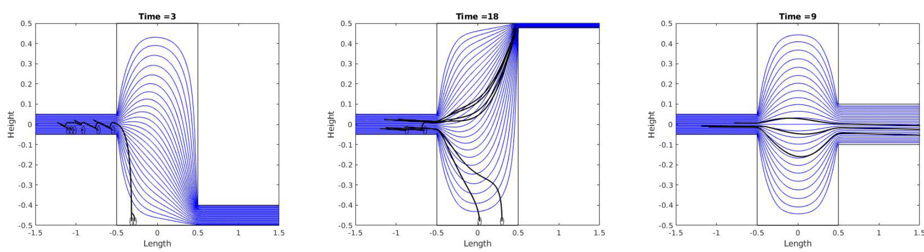


Figure 3 – Model for a fine trapped by a piece of asperity

A fine is released when the combined gravity and drag forces point over the asperity.

Our model involves a simple force and torque balance on the fine. At the point that the fine is about to move, the normal and frictional forces at the pore wall drop to zero and we find that the fine is released precisely at the point where the combined gravity and drag forces point towards the asperity. From this we calculate the velocity required to release a fine of a given size, assuming a specific asperity size.

3. Results



(a) 2 micron fines; average input flow 3×10^{-6} m/s **(b) 2 micron fines; average input flow 3×10^{-4} m/s** **(c) 3 micron fines; average input flow 3×10^{-3} m/s**

Figure 4 – Example trajectories of fines (shown in black) along with streamlines of the flow (shown in blue)

We solve for the fluid flow through the pore and throats using COMSOL and then solve for the trajectories of individual fines using Matlab. In figure 4 we show some typical fines trajectories. We see that the particles don't follow the streamlines in any of these simulations and that some particles are trapped in the pores when the flow is slow. We consider three metrics: whether pore blocking occurred; what fraction of fines were deposited; and how many pores a fine will travel through before being deposited.

In order to compare how often the pore blocks, we consider nine different geometries. Specifically, we fix the left hand throat to have a diameter of 10 microns and be at the centre of the pore. We allow to the right hand throat to have a diameter of 2, 10 or 20 microns and be positioned at the bottom, center, or top of the pore. For each of these geometries we consider five velocities: 3×10^{-6}, 3×10^{-5}, 3×10^{-4}, 3×10^{-3}, and 3×10^{-2} metres per second. We consider fines of 2, 3, and 4 micron radius. In figure 5, we present the results of multiple simulations. The colour of each point indicates the "blocked state" at the end of the numerical simulation, indicating if the pore blocked (yellow), did not block (red) or if no fines reached the right hand pore (green). In order to ensure the results were comparable, and as our model is two dimensional, we fix the total amount of fines material. We see from our results that blocking of pores depends very little on the relative heights of the throats, but is highly dependent on their diameter. This is not surprising since, for a small diameter throat, the fines will simply not be able to fit through. We also note that there is little difference between different sizes of fine, but this is likely due to to the fact that all fines chosen here are

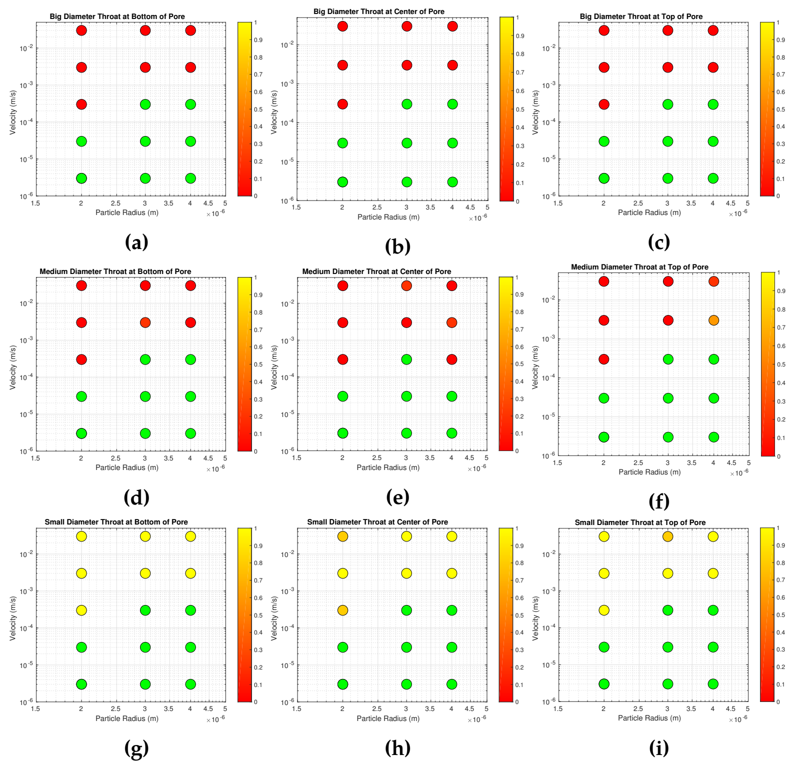


Figure 5 – Graph showing the amount of blocking. Green dots represent simulations where no fines reached the right hand side of the pore, red to yellow dots show the fraction of simulations in which pore blocking occurred, with the colour bar showing said fraction

larger than the smaller throat size. If we were to do more simulations with different throat sizes we would expect to see a closer coupling between throat size and particle size.

To find the fraction of fines deposited, we consider the same geometries, velocities, and fine sizes as in the blocking case. We calculate the fraction of fines that were deposited and the results are shown in figure 6.

Blocking occurs when the diameter of the throat is small.

We colour each point green if no fines made it to the right pore, yellow if all fines are deposited, and red if no fines are deposited. We see that, as with the blocking case, deposition of fines varies very little with the relative height of the throats. Further, we see that the fraction of particles deposited decreases with velocity. We also see that, for the smallest size of throat diameter, all fines are deposited. This is because either the fines could not move and were never deposited, or they could and blocked the throat.

If the velocity is too low, fines will not travel far enough to reach the right hand side of the pore.

In order to assess how many pores a fine of a given size will travel through, we randomly generate a porous pathway from our three geometries and we iteratively solve the model in order to determine how many pores a fine passes through. We show the results in figure 7. We see that the number of pores travelled depends a huge amount on the size of the fine and the velocity. As can be expected, the higher the fine is initially the more pores it will travel through, since it takes longer for gravity to pull it down to the bottom of the throat, where it will be deposited.

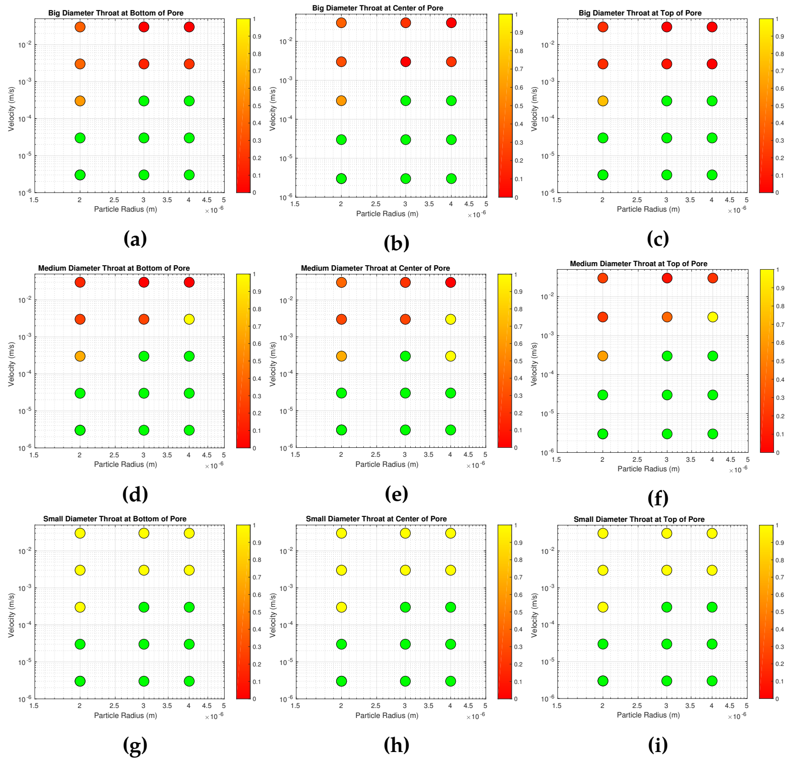


Figure 6 – Graphs showing the amount of material deposited. Green dots represent simulations where no fines reached the right hand side of the pore, red to yellow dots show the fraction of fines that were deposited with the colour bar showing said fraction

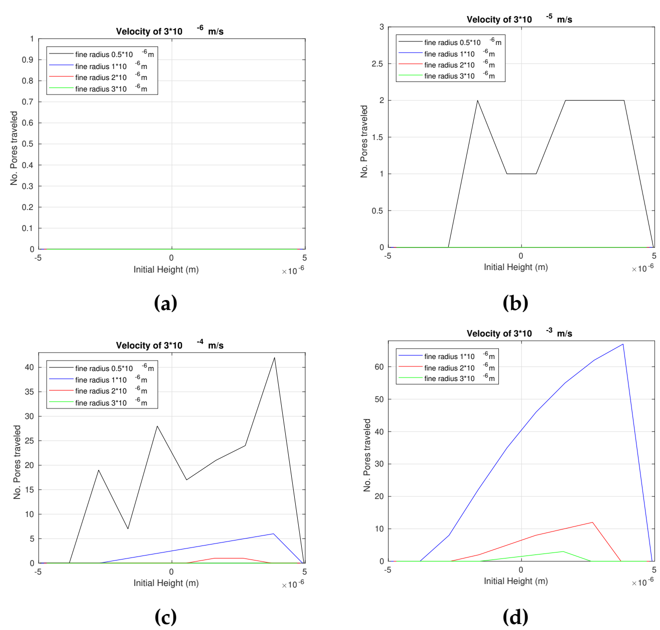


Figure 7 – Graph showing the number of pores travelled by a fines particle

4. Discussion, conclusions & recommendations

We have developed a model for fines migration, which we have solved numerically, using COMSOL for the fluid flow and Matlab for the fines trajectories.

Our results show that the fluid velocity, pore throat diameter, and fine size are key factors in the migration and deposition of fines. We identify two important regimes: a regime in which the fluid velocity is too slow for the fines to leave a single pore and a regime in which fines are mobilized and can exit. In the latter case, we also explored the distance an individual fine will travel before becoming trapped.

We also modelled the generation of fines within a reservoir by considering a single spherical fine trapped in place by an asperity. We find that the fine is released at precisely the point when the combined gravity and drag forces point towards the point of contact between the fine and said asperity.

There is is a large amount of further work to be done in this area. Specifically, there is a need to extend our model in a number of ways, which we list below:

- couple the motion of the fines with the flow of the fluid,
- include a more physically realistic process by which the fines stick onto the walls of the pore,
- add electrodynamic affects,
- consider the effects of the distribution of pore and fines sizes,
- study the effects of having multiphase fluids in the porespace,
- extend to a multipore model.

It is recommended that BP continue to research the affects of fines migration on oil recovery in order to gain better insight on the mechanics of this phenomenon.

5. Potential Impact

Permeability reduction, caused by fines migration, has a significant impact on oil recovery. The development of mathematical models to describe this is an important step in understanding how this process works, which will help to drive insight on how to effectively manage this problem. Our work serves as a preliminary step in developing a full model to describe the migration of fines in an oil reservoir and their impact on permeability.

Bilal Rashid, Reservoir Physicist, BP said: "*Formation damage is a long standing issue in oil field operations, both during conventional water injection and during fresh/river water injection. This leads to a real reduction in oil production. To date there are no robust mathematical models to describe the behaviour of fines in porous media and limited tools to understand the interaction between flow velocity, particle size and shape, and pore geometry. This work has already shown how velocity, particle size and some simple geometries interact to cause permeability reduction and we look forward to the PhD project to provide a real insight into these damage mechanisms.*"