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IN-SITU PARTICLE MIGRATION AND PLUGGING MECHANISM IN UNCONSOLIDATED SANDSTONE AND SANDING MANAGEMENT

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Rock particles can easily become mobile and migrate in poorly cemented sandstone in a heavy-oil reservoir because of their higher density and viscosity. Deposition of the solid particles clog and bridge the pores and pore throats, leading to increased filtration resistances in the reservoir and decreased well output. In this work, we studied the process of particle migration and pore blockage under a microscope using an unconsolidated sandstone model. We studied the mechanism for migration of fine particles and their effect on the percolation capacity of a porous medium by monitoring the dynamic permeability in a poorly cemented sandstone sample, containing a mixture of particles of different sizes. We have shown that the change in permeability with particle migration depends on the size and type of the mobile particles and pore throats, the concentration of the migrating particles, the total number of particles, the pressure drawdown or fluid flow velocity, and the reduction in maximum permeability, while the clogging transition time is determined by the minimum size of the bridging particles. As an example of field application, we consider a strategy for oil production with sand control.

Key words: *unconsolidated sandstone, particle migration, laboratory studies, production with sand control.*

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The migration of rock particles together with in-situ fluid through a porous medium of poorly cemented sandstone is a common phenomenon in a heavy-oil reservoir because of weak cohesion or lack of cohesion between particles, making it easier for them to move together with high density and high viscosity oil. The processes of onset of particle movement, migration, settlement, and retention of particles in pores depend on the entrainment capacity of the in-situ fluid flow during reservoir exploitation; accordingly, the permeability of the formation and the productivity of the well can be varied by different methods.

The influence of particle migration on production decline in wells is well known [1]. Studies have been conducted on the mechanism for generation of mobile rock particles [2] and the mechanism for formation damage resulting from migration and deposition of particles [3]. It has been found theoretically and experimentally that the in-situ fluid velocity, the entrainment capacity of the flow, the ratio of the particle sizes to the pore throat sizes are key factors in migration and plugging of the porous medium by rock particles [4]. In some cases, the hydraulic conductivity of the formation can be affected by outward migration of particles [5, 6]. Most recent studies have targeted clay minerals [7, 8], asphalts, solids in the injection fluid, grains produced by physical and chemical reactions due to incompatibility of the injection fluids, the formation fluids, and the rocks. The primary focus of these studies has been the near-wellbore area with high-speed fluid streams or perforation holes [9].

There have been few reports of studies on potential migration of particles and their influence on flow in poorly consolidated or unconsolidated sandstone. In many cases, experiments on visualization and simulation of migration and clogging for particles have been conducted on a glass microscope slide or in a polymer etching (polarized image) model with capillary networks. However, such a model cannot be used to simulate a real unconsolidated sandstone with an unstable structure.

The stability of sandstones was studied using triaxial core testing under different loads in a two-phase medium consisting of oil and water [10, 11]. It was shown that this stability depends on the particle

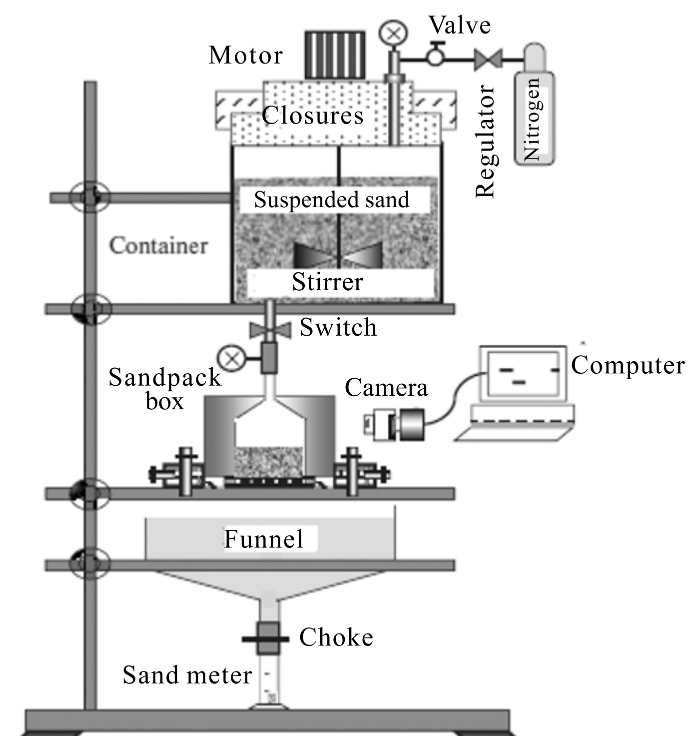

Fig. 1. Experimental setup for microanalysis

Table 1

No	Size, μm	Grain size distribution in sandpack, wt.%		
		Sample 1	Sample 2	Sample 3
1	500-1000	7.58	3.88	20.38
2	250-500	15.03	7.77	40.76
3	125-250	32.78	46.60	15.50
4	80-125	19.84	31.07	14.01
5	60-80	12.20	7.77	6.79
6	40-60	7.09	1.94	1.71
7	20-40	5.48	0.97	0.85
D_{50}, μm		210	180	355

size in the sandstone and the saturation by the wetting phase, and this discovery is now applied to the sand control process in rocks of a certain strength. The critical conditions for particle migration and plugging of pore throats, including particle sedimentation and its influence on the flowing pressure at different flow rates and different particle concentrations, were studied using a microcapillary model with different diameters [12].

However, the details of the mechanism described for the flow process in a capillary are quite different from what occurs in an actual porous sandstone. Experimental evaluations of formation damage caused by migration and pore plugging by sand particles are usually conducted by studying displacement of fluids in a short sandpack tube [1, 4, 13, 14]. However, systematic errors were inevitable due to the presence of too few particles, which made it difficult to obtain measurements of movements within this small core column, leading to certain errors in the experimental results.

In this study, the process of setting the rock particles into motion, accompanied by their migration, sedimentation, and plugging in actual pore tunnels of unconsolidated sandstone was simulated and observed with the help of a microscopic sand pack visualization model. Furthermore, the inflowing process in an actual formation was simulated by continuous injection of a sand mixture into the model for poorly cemented sandstone (the sandpack tube). In this procedure, the influence of particle migration and plugging in a porous medium was analyzed according to the dynamic changes in permeability, which were monitored under different injection conditions.

It has been established that the well productivity will decline as the rock particles migrate and clog pores in the unconsolidated sandstone reservoir. In order to achieve stable production, typically three methods are used to prevent formation damage from particle migration: optimization of well completion taking into account sand control; acidizing near the wellbore; increasing the stability of the grain structure by tackifier injection [15]. However, the effect of these strategies is significantly reduced in a heavy-oil sandstone reservoir, since generation of mobile sand particles is inevitable due to the instability of the rock skeleton close to the wellbore and erosion of the rock skeleton in poorly consolidated or unconsolidated formation during flow of the viscous fluid.

The experimental setup for microvisualization consists of a hollow and transparent high-strength sand pack box, a container for the fluid, a stirrer with a motor, a sand meter, and a computer system (Fig. 1).

The transparent container was packed with ordinary river sand, which was sieved according to the grain size distribution in an actual unconsolidated sandstone, as shown in Table 1.

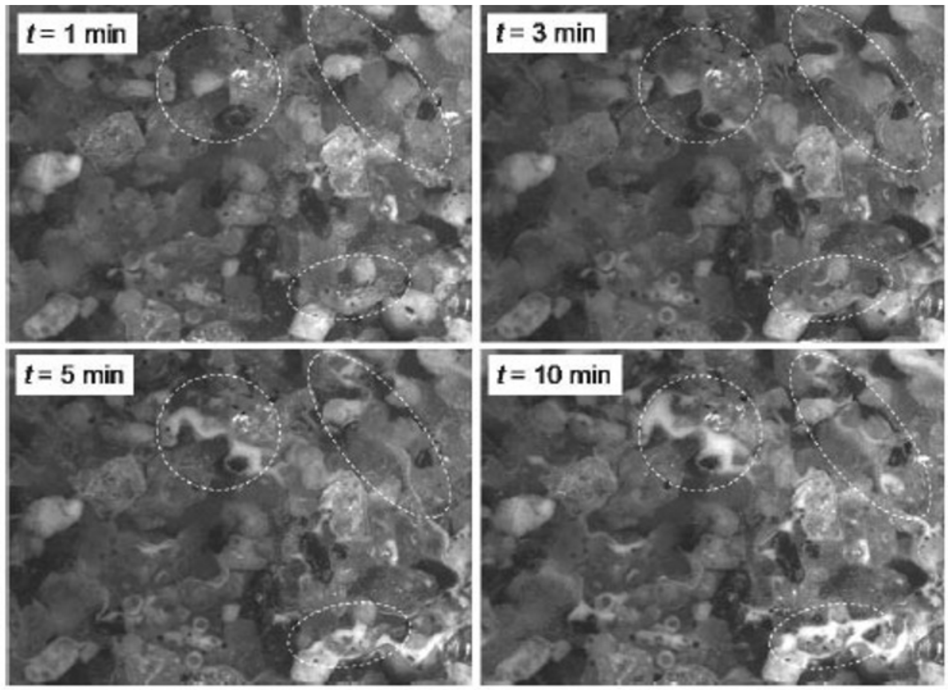

Fig. 2. Clogging in tunnels during injection of sand-containing mixture.

The fine quartz sand with median particle size (d_{50}) of about 20 μm was mixed with a 1% solution of guar gum thickener as substitutes for respectively mobile rock particles and viscous heavy oil in the actual formation. Before the experiment, the sand container was first slowly immersed in water, starting with submerging the lower part of the box and gradually displacing the air upward. Then the components were assembled according to the diagram shown in Fig. 1. The liquid flow velocity was adjusted with the inlet valve, and the processes of particle migration and pore clogging were observed and recorded using a microscope camera.

The particles migrating through the porous medium and plugging the pores were observed and analyzed during injection of the mixture with a denser mesh at the exit end of the sandpack box, as shown in Fig. 2. On the other hand, clearing of the tunnels as the fine particles were dislodged was recorded during injection of fresh water (Fig. 3). We observed migration of fine particles and the different ways in which they clogged the pores and tunnels while pumping sand-containing mixtures of different particle size distributions and at different flow velocities.

The nature of the particle migration and pore plugging in the unconsolidated porous medium was analyzed based on images obtained using a microscope. We obtained the following results.

1. The particles could not enter all the tunnels, since the migration path depended on the particle size and shape of the particles and on the tunnel shape.

2. Particle sedimentation occurred in tunnels when the flow velocity was low.

3. As the flow velocity increased, the particles changed from being at rest to being in motion in a certain sequence: rotating in-situ, moving intermittently in the tunnel, “jumping,” and moving with the fluid flow. More particles participated in this motion at higher flow velocity.

4. Pore bridging occurred, and further plugging was induced by a decrease in flow rate and entrainment capacity of the flow.

5. Bridging and clogging initially occurred as a result of large particles, which eventually completely blocked the interior of the tunnels.

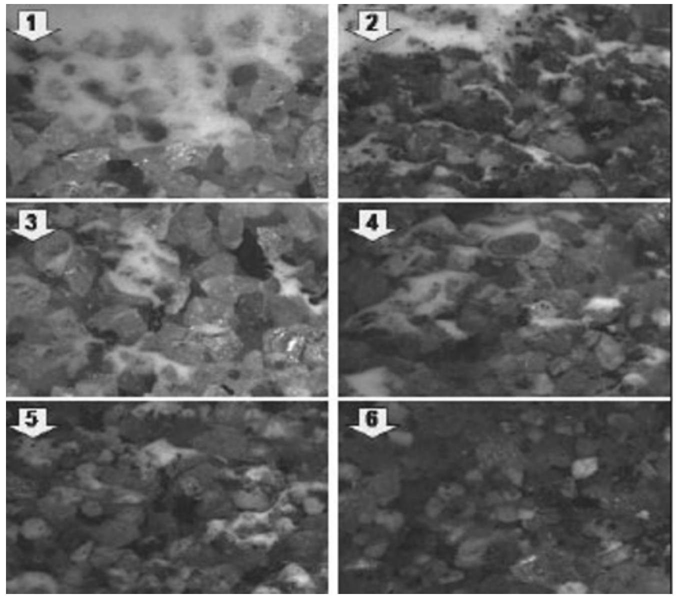

Fig. 3. Clearing in tunnels during injection of water.

6. Settling of the particles occurred when the flow velocity decreased in a tunnel of large radius; the particles became mobile again when the flow velocity increased.

7. In the unconsolidated sandstone model, the stability of the rock skeleton was poorer as the particle size became smaller, due to the more limited range of particle motion.

8. At faster fluid flow, more finer particles were entrained and the rock skeleton could incur more damage. A larger range of particle motion and a shorter clogging transition time were achieved with faster fluid injection.

9. New mobile particles appeared in the rock skeleton when the injection rate was changed, indicating collapse of the plugging zone formed in the tunnels.

A certain amount of cement powder was added to the sand pack to obtain a mixture consistent with the grain size distribution in an actual unconsolidated sandstone sample. The sand pack simulating an unconsolidated sandstone formation was prepared by soaking it in water and drying at room temperature, following by porosity and permeability measurements. Fine quartz sand, with median grain size (d_{50}) that was 1/6 and 1/4 of the median grain size in the rock skeleton (D_{50}), remained in the container. The sand was mixed with a 1% solution of guar gum and suspended by continuous stirring. The concentration of solids in the solution was set at 10 ppm, 100 ppm, 200 ppm, and 500 ppm. Different amounts of fine particles were suspended in the viscous fluid and continuously injected through the sand pack, in order to simulate inflow in an actual formation near the wellbore. The influence of particle migration through the medium and clogging in the tunnels on the flow capacity in the porous medium was evaluated by monitoring the decline in permeability during injection of mixtures with different particle sizes.

The permeability was significantly reduced with continuous injection of the particle mixture (Fig. 4). Obviously the permeability was decreased uniformly for solutions with lower particle concentrations, such as for 100 ppm. However, the proportionality of the decrease in permeability changed for higher particle concentrations, such as for 200 ppm or 500 ppm. In the initial phase, we observed a relatively rapid decrease in permeability, but the decrease gradually slowed down. This process was more obvious during injection of a solution with larger particle sizes ($d_{50} = 1/4D_{50}$).

Problems associated with particles bridging and clogging the tunnels were less severe during injection of the composition with a higher concentration of solids, when the permeability declined rapidly. On the other hand, invasion by particles injected in a later stage was prevented by the earlier blockage, and as a result the decrease in permeability slowed down.

The main factors reducing the permeability during particle migration include the size ratio between the mobile particles and the tunnel diameter, the particle size distribution (size sorting), the suspended particle concentration in solution, the total number of transported particles, and the flow pressure gradient or flow velocity. They are explained as follows:

1. Median particle size (d_{50}): larger particles in the tunnel accumulated and clogged the space, but they also could prevent further invasion by solids.

2. Minimum particle size (d_{90}): According to the bridging principle, the lowest flow capacity in the blockage zone in a porous medium was determined by the minimum size of the mobile particles.

3. Sorting: faster bridging and clogging was achieved with a broader particle size distribution.

4. Concentration: Higher concentration of solids in the solutions for the same particle sizes more rapidly led to bridging and clogging of the porous medium.

5. Injection time: The total number of particles entering the rock depended on the concentration of solids in the injected solution, the flow velocity, and the total injection time. Clogging in the tunnels occurred in the final stage, when the total number of particles in the rock was sufficiently high.

6. Pressure gradient: The injection velocity and the total number of mobile particles depended on the pressure gradient. However, the bridges formed in the tunnels could break down at a certain pressure, because the rock skeleton was unstable (unconsolidated sandstone model). Consequently, the permeability was temporarily enhanced until the next bridging and clogging occurred.

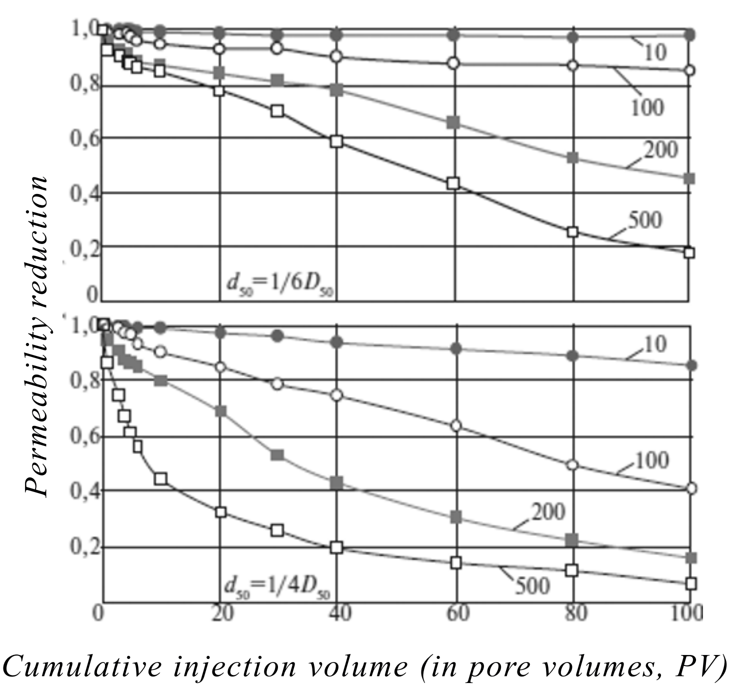

Fig. 4. Permeability reduction during injection of solution No. 1 (a) and No. 2 (b) with different particle concentrations (see numbers on curves).

In-situ particle migration inevitably occurs in heavy-oil reservoirs consisting of poorly cemented sandstone, due to the poor cohesion between particles and the high viscosity of the formation fluid. In a poorly cemented formation, the major source of sand particles carried away with the oil are free particles generated due to various factors. In the near-wellbore area, there is a higher concentration of mobile particles due to the greater entrainment capacity of the fluid with higher flow velocity in a region of smaller radius. Significant in-situ blockage of the tunnels occurs because the mobile sand particles do not pass through the protective screen, consisting of small particles used to prevent sand production.

More fine particles accumulate and since the minimum in-situ flow capacity in the tunnels depends on the minimum particle size in the protective screen (bridging sand particles), the permeability close to the wellbore will decrease sharply, which leads to rapid and significant decline in well productivity due to bridging and clogging of tunnels by the migrating particles.

Since the minimum permeability depends on the minimum size of particles blocking the tunnels, a smaller reduction in the in-situ flow capacity can be achieved if the minimum size of the particles forming a protective screen (bridging particles) is increased. This presumes that oil production with sanding control is needed.

The main principle of oil production with sanding control involves the following. The mesh size of the sand-control screen used for well completion is selected taking into account the size and type of mobile particles in the formation, and so particles smaller than the mesh can pass through the screen and be transported to the surface with the reservoir fluid. Blockage of the tunnels in the rocks and the degree of permeability decline obviously are reduced due to the relationship between the protective screen (bridging particles) and clogging of the porous medium, since fine particles carried away from the formation are smaller than the minimum size of the protective screen (bridging particles) used for sand control. Furthermore, total sand production is decreased, since sand control is still effective for larger particles. The main contribution of this sand management strategy involves the enhanced or partially recovered well productivity, and also sand production that is under control. From this point of view, offshore oil companies can use this strategy to limit sand production in wells.

It is very difficult to achieve ideal production using reduced sanding in actual oil reservoirs, because of the complex structures of the tunnels in the rock, the different sizes and shapes of the tunnel cross sections and the mobile particles, and the general heterogeneity in actual reservoirs. Blockage is the final stage in the service life of each tunnel in the rocks, and well productivity declines due to particles inevitably clogging any poorly cemented heavy-oil reservoir. However, this negative influence can be reduced if migration of fine particles is reduced.

The key technologies included in this strategy are the following:

1. Optimization of sand control parameters: Since the final well productivity depends on the minimum size of the sand fraction used as the filter (the bridging sand), it is more important to choose an appropriate type of well completion with sand control based on reservoir characteristics such as rock cohesion, size distribution and sorting of mobile and potentially mobile particles, sizes of tunnels in the rock, and the fluid properties.

2. Optimization of the constraints in the flowing well: The number of mobile particles and the range of the zone where mobile particles appear are determined by the fluid flow velocity and the pressure gradient in the reservoir. The bridging and clogging dynamics in the tunnels of the rock depend on the size, distribution (sorting), and concentration of the solids. Therefore the well productivity mainly depends on the current

production rate under the same in-situ reservoir conditions. We concluded that the optimized production rate and pressure drawdown for maximum processing capacity can increase well productivity.

From the results of the study, we can draw the following conclusions.

1. In unconsolidated sandstone, the number of mobile particles and the range of the disturbed zone due to motion of solids and the permeability decline are determined by the particle size, particle distribution (sorting), and particle concentration plus the fluid flow velocity in the tunnels.

2. The final permeability of the blockage zone depends on the minimum bridging particle size and on the degree of clogging in the tunnels. Based on these principles, we suggest that the reservoir will provide production containing a solid phase, i.e., some fine solids will be carried away from the formation and be transported to the surface together with the fluid.

3. Clogging and clearing are simultaneous effects of particle migration in an unconsolidated sandstone porous medium. Both these effects occur in a production well with sanding. To manage sanding and reduce production decline, we use a sand-control screen with a certain mesh size.

We propose the following sand control measures:

1) In the early production phase, a short-term production period or drawdown is needed to make the rock skeleton lose stability and to rapidly bridge the reservoir close to the wellbore, containing larger particles; this also can prevent or delay clogging of tunnels by fine particles produced in the later stage and carried away from the formation.

2) High-pressure pulsed injection to enhance the efficiency of the well in a later stage, in order to release most of the particles clogging pores and tunnels close to the wellbore.

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