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Numerical Simulation of Sand Production Using Coupled DEM-LBM

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ABSTRACT: Sand production imposes a considerable cost on the oil industry. In the current study, this phenomenon is studied numerically to better understand the particulate mechanism of sanding in unconsolidated sandstones and study the effect of confining stress and pressure drawdown on sand production. The discrete element method (DEM) is used to simulate the particulate media, and the lattice-Boltzmann method (LBM) is adopted to model the fluid flow through it. The two methods are coupled, and the fluid-solid interaction is modeled using the immersed moving boundary (IMB) method. An in-house computer program is developed based on these methods to simulate the 2D sanding procedure under radial fluid flow and isotropic stress in the absence of particle cementation. The results show that the number of produced particles and the sanding rate increase with the increase of confining stress. Also, after the sand initiation, the sanding rate in all models decreases due to the formation of sand arches around the model's inner cavity. These arches are prone to instability, and new larger arches replace them after their collapse. After examining the effect of fluid pressure difference on sand production, it is concluded that the pressure difference has little influence on sand production at relatively low-stress levels. However, at higher stress levels, the pressure difference has a considerable impact on sanding results as it increases the number of produced particles more than twice with a 50% increase in pressure difference. This study confirms that the 2D coupled DEM-LBM model can properly capture the mechanism of the sand production phenomenon.

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1- Introduction

Sand production is an undesirable phenomenon, consisting of the detachment and transport of solid particles from the formation during the extraction of hydrocarbons. Sand arches are considered responsible for preventing sand production in unconsolidated formations [1]. Researches on sand arch stability have shown that many parameters, including initial arch diameter [2] and fluid discharge, may impact the sanding phenomena in unconsolidated sandstones.

It is argued that the actual sanding mechanism in wellbores is not accurately captured in sand arch stability studies. Thus, the thick-walled hollow cylinder (TWHC) test is used to better simulate sand production [3]. In these tests, the samples are under the impact of increasing confining stress and radial fluid flow. These experimental studies showed that with increased stress levels and fluid pressure drawdown, the sanding intensifies, and more particles are produced [1].

Although many numerical studies addressed the sand production phenomena, the particulate nature of sanding in TWHC samples is not properly studied. Also, in most numerical studies, the radial fluid flow is not simulated, and the flow conditions are oversimplified. In the current study, the particulate mechanism of sand production is studied in 2D cross-sections of TWHC samples subjected to radial fluid flow. DEM simulates the solid phase, and it is coupled with the LBM, which is used to model the fluid flow through the porous media. In addition, the effects of the confining stress and the pressure drawdown are specially addressed.

Methodology

DEM models the behavior of distinct particles in a granular assembly to simulate its macroscopic behavior. In this method, a series of consecutive calculation cycles are performed to determine the new position of the solid particles based on the forces acting on them. After the boundary conditions are applied, the contact forces between the particles are calculated using the contact law, determining the interparticle forces based on the particle overlaps. Then, the resultant force and moment are calculated at the center of each particle and are later used in the motion law. It expresses Newton's second law for each particle, as their acceleration, velocity, and displacement are determined.

LBM is a numerical method for simulating the Navier Stokes equations for nearly incompressible fluids. The step-by-step computational mechanism of the LBM has made it

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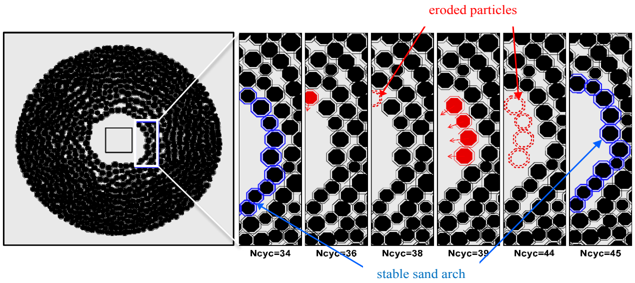

Fig. 1. The instability process of the particle assembly adjacent to the inner cavity in particulate scale

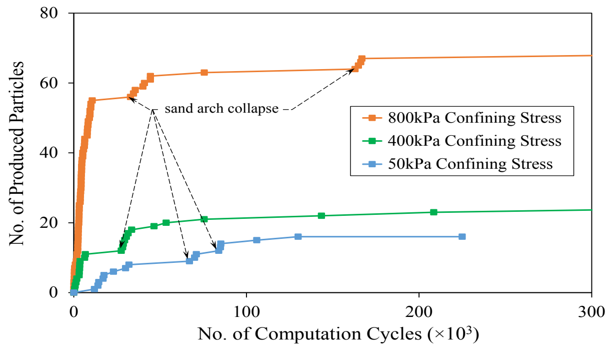

Fig. 2. A schematic view of the DEM model and the approximate location of the fluid inlets/outlets

relatively easy to be coupled with the DEM. In LBM, the fluid medium is assumed to be a set of virtual particles located at the nodes of a regular network called "lattice". As the fluid particles propagate throughout the domain, they collide with each other. This collision and propagation form the fluid flow behavior [4].

To couple the two numerical methods, an approach called Immersed moving boundary (IMB) method is used in which the collision operator of LBM is reformulated to better model the solid-fluid interaction in dense multiphase media [4, 5]. Also, The hydrodynamic force (moments) acting on each solid particle is added to the resultant force (moment) calculated from the contact law.

Results and Discussion

The validation of the computer program developed upon the coupled DEM-LBM included simulating the sedimentation process of a single solid particle in a fluid-filled container. After comparing the results with those of the previous studies [6], the accuracy of the developed program in simulating fluid-solid interactions is approved.

Then, the sand production tests are conducted on donut-shaped models replicating cross-sections of TWHC samples. The model generation is performed in the following steps: 1) 1500 non-overlapping octagonal particles are generated with relatively uniform distribution and mean diameter of D_{50}=2.5mm, 2) the generated particles are compacted by applying limited boundary displacement, 3) the compacted assembly is relaxed by removing the applied strain and allowing the rearrangement of the assembly particles, 4) a 50kPa confining stress is applied to the assembly boundaries, 5) a 20mm diameter hole is drilled in the center of the assembly by deleting all the particles whose center of gravity are located in a 10mm radius of the middle of the model, 6) while the applied confining stress is maintained, the radial inward flow runs through the porous media with a prescribed pressure drawdown, and 7) after the sanding rate is negligible, the isotropic stress is increased to 400 and 800kPa, and the last two steps are repeated for the new stress values. Similar to previous 2D numerical studies [6, 7], a parameter called the "hydraulic radius multiplier" is introduced to virtually shrink the actual size of particles in LBM simulation and consequently facilitate the fluid flow through adjacent particles.

After examining the sanding process on the particulate scale, it is confirmed that the sand arching is the sole resistant factor against erosion as there is no cohesion or interparticle bond between solid particles. At 10kPa pressure drawdown, after limited sand production, a stable arch is developed around the inner cavity. The arch is stable until the pressure drawdown increases to 15 kPa when the arch becomes unstable and is later replaced by a larger one, as anticipated by [2, 7] (Figure 1). The results confirm that the arch instability in unconsolidated sandstones results in sand production.

The results also indicate that with the increase of confining stress, the amount of produced sand increases (Figure 2). Furthermore, it is concluded that the sanding rate increases with the increase of confining stress. However, over time, similar to previous studies [8], the sanding rate in all samples decreases due to the formation of stable sand arches around the inner cavity.

Mixed results were obtained about the effect of pressure drawdown on sand production. At low-stress levels (50 and 400kPa), the increase in pressure drawdown showed little impact on sanding results. However, following previous experimental studies [1, 9], at high-stress levels (500kPa), the increase of pressure drawdown from 10kPa to 15kPa significantly increased the number of produced particles.

Conclusions

Despite its 2D nature and relative simplicity, the numerical model can properly simulate sand production and its affecting parameters.

With the increase in stress level, the amount of produced sand and the sanding rate increase.

Shortly after the initial sand production, due to the formation of stable sand arches around the inner cavity, the sanding rate decreases.

Due to the increase of pressure drawdown or stress level, the initial stable arch collapses, accompanying considerable sand production. However, a new larger stable arch is usually formed afterward.

Although the effect of pressure drawdown on sanding was found negligible at low stress levels, a 50% increase in pressure drawdown at higher stress levels doubles the number of produced particles.

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