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Coupled solid and fluid mechanics modeling of formation damage near wellbore

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ABSTRACT

The infiltration of drilling mud below the bit and into the wellbore wall causes pressure gradients that significantly degrade drilling performance, wellbore stability and production. Due to heterogeneity, standard constitutive relationships and models yield poor predictions for flow (e.g. permeability) and rock properties (e.g. elastic moduli) of the invaded (damaged) formations. This severely reduces our ability to, for instance, estimate pressure build-up, optimize the mud cake properties or predict rock mechanical behavior.

We propose a numerical model for permeability estimation in damaged formations near wellbore (e.g. sediments invaded by fines or sand crushing remnants). Grains of two length scales are present, but only larger ones are load-bearing. Detailed cemented granular packs were modeled using a discrete element method software, and ensuring mechanical stability. The particle positions and arrangement were available for subsequent pore throat network analysis. The standard network modeling approach for analysis of packing of nearly equal grains (Delaunay tessellation) cannot be used since grains of two different length scales create a high fraction of distorted pores. The main novelty of this work is adapting the network flow model to work with two length scales, and we present both the network creation and flow model in the multi-scale case.

The effects of particle size and initial formation porosity on formation damage are studied in detail. Our study confirms that large particles tend to occupy the formation face, while small particles invade deep into the formation. Moreover, particles which are smaller than pore throats (entrances) impair permeability more than those larger than pore throats. Our study also indicates that a higher initial formation porosity leads to more particle invasion and permeability impairment. Thus in order to reduce formation damage, mud particle size distributions should be carefully selected according to given formation properties.

1. Introduction

1.1. Formation damage overview

Formation damage is a common problem in petroleum reservoirs, and happens in different stages of reservoir development from drilling to production. The causes of formation damage include particle invasion, formation fines migration, chemical precipitation, and pore deformation or collapse (Liu and Civan, 1996). Formation damage adversely affects production of petroleum reservoirs by reducing the permeability of the near wellbore region (see Fig. 1). A small zone of reduced permeability often greatly reduces the productivity of a petroleum reservoir. Furthermore, formation damage also affects well logging results, because most well logging tools can only measure the data within a rather shallow region that is most likely damaged. Therefore, understanding the mechanism of formation damage and the factors controlling its severity are vital for improving the accuracy of formation evaluation and the efficiency of reservoir production. Well testing techniques provide approaches to determine formation damage near the wellbore. However, those techniques only provide the skin factor as an overall measure of the formation damage (Liu and Civan, 1996). Mathematical models combined with laboratory studies can help provide insights into the spatial development and causes of formation damage.

There are many experimental studies on formation damage in petroleum reservoirs (see below), but few reported mathematical models of this process. The published models can be categorized into two major groups: macroscopic and microscopic models. Macroscopic models do not represent pore scale dynamics of filtration and the clogging of pores due to infiltration in detail, but hope to capture average behavior. Microscale network models,

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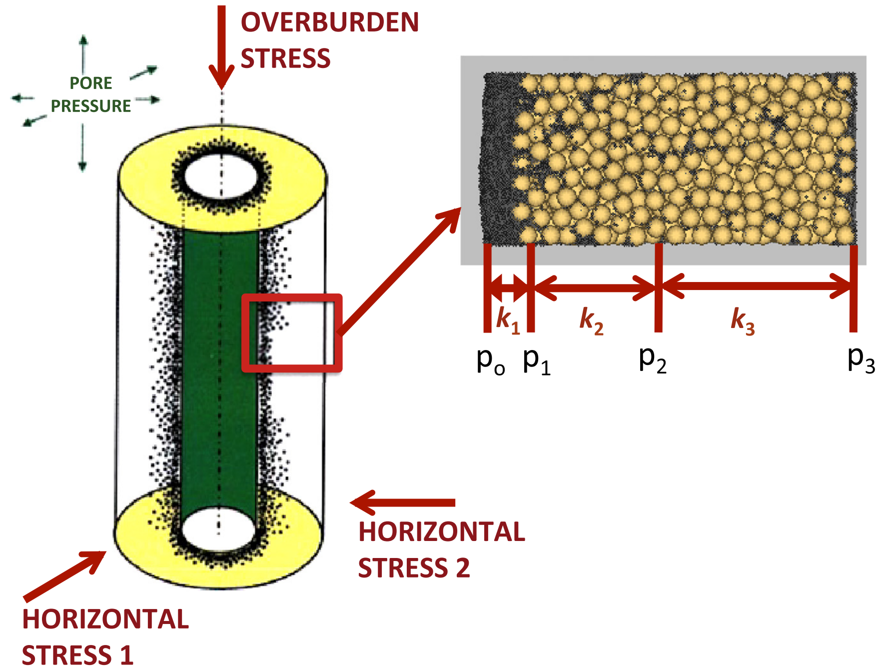

Fig. 1. Infiltration of drilling fluid (containing weight control additives and crushed rock, shown as black particulates) into the formation near wellbore (in the enlarged schematic on the right, formation grains are shown in yellow). As seen in the enlarged section on the right, the concentration of solids is the largest near the wellbore wall, and decreases with depth creating regions of different porosity, permeability *k* and end-point pressures *p*. Schematic exemplifies three such regions, though in reality change in permeability is continuous. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

on the other hand, are means to model pore scale geometry and can incorporate details of the transport and deposition processes. However, exact theory for interaction of particles and pore-grain surface of general shape is not known, and thus models typically assume spherical particles and locally straight interfaces.

1.2. Macroscopic models

One of the earliest macroscopic models are deep bed filtration (DBF) models (Herzig et al. 1970). DBF models evolve concentration fields, and assume macroscopic flow continuity and mass balance. The key to the modeling is the knowledge of kinetic equation for evolution of porosity. Most recently, DBF models were compared with experiments (Boek et al., 2011), and a broad agreement was obtained, but the experimentally observed non-monotonic permeability/porosity reduction cannot be matched. This is the key problem in macroscopic models (including the bundle of tubes approach by Wojtanowicz et al. (1987), and a well-mixed compartments model by Khilar and Fogler (1987)): they presume relationships between averaged parameters (such as porosity/particle concentration or permeability/porosity) are known in advance without providing the ability to investigate them by studying fundamental mechanisms.

1.3. Microscopic models

Fatt (1956) was the first to introduce an interconnected network of tubes as a means to study fluid behavior in a porous medium. Network models have since explained various phenomena in porous media, such as entry pressure, residual saturation, permeability and resistivity (for overview see Blunt (2001)). As opposed to early models which used regular lattices, modern network models use a physically representative network. For granular media, Delaunay tessellation is a common method of pore-throat network construction, and we describe it in some detail below. Representative network models can be derived from imaged consolidated porous media (Øren and Bakke, 2003; Prodanovic et al., 2006), but those methods are not applicable to our samples. Sharma and Yortsos (1987) were the first to employ network models (where the porous medium is represented by a network of pore bodies and pore throats) to study damage. They considered two mechanisms of permeability reduction: (1) particles larger than pore throat block the flow and (2) particles much smaller than the pore throats are deposited and reduce the size of the pore throat gradually. However, dynamic change in throat sizes makes is difficult to accurately predict or validate permeability using the effective-medium approximation. Rege and Fogler (1988) developed a 2D network model that uses the concept of flow-biased probability for the movement of particles through different flow paths. The effects of various network size, particle size distribution and pore size distribution, on permeability reduction were studied. Parameters used, however, require adjusting to the experimental data which makes the model computationally demanding.

Bortal-Nafaa and Gouvenot (2002) identified pore clogging as the dominant damage mechanism during cement operations. The authors created a sandstone specimen using the discrete element method (DEM) and tuned it to match the macro-mechanical behavior of the real sample. Instead of modeling details of the fluid flow, the drag force was exerted on infiltrating cement particles. The drag force depends on the relative velocity between the fluid and the particle it is transporting, and the size of the suspended element. The numerical simulation results were compared to the experimental results and found to fit very well. Kim and Whittle (2006) used incompressible Stokes' flow equations to simulate pore-scale particle deposition and clogging. The invading fine particles were under the influence of hydrodynamic and gravitational forces, and assumed to settle at velocities according to Stokes' law and attach to surfaces using a probability model. The model geometry was very simple (single cylindrical pore) due to computational demands, though a large number of numerical simulations were conducted to show that the particle collect-