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Simulations of the effects of proppant placement on the conductivity and mechanical stability of hydraulic fractures

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ABSTRACT

We generate a wide range of models of proppant-packed fractures using discrete element simulations, and measure fracture conductivity using finite element flow simulations. This allows for a controlled computational study of proppant structure and its relationship to fracture conductivity and stress in the proppant pack. For homogeneous multi-layered packings, we observe the expected increase in fracture conductivity with increasing fracture aperture, while the stress on the proppant pack remains nearly constant. This is consistent with the expected behavior in conventional proppant-packed fractures, but the present work offers a novel quantitative analysis with an explicit geometric representation of the proppant particles. In single-layered packings (i.e. proppant monolayers), there is a drastic increase in fracture conductivity as the proppant volume fraction decreases and open flow channels form. However, this also corresponds to a sharp increase in the mechanical stress on the proppant pack, as measured by the maximum normal stress relative to the side crushing strength of typical proppant particles. We also generate a variety of computational geometries that resemble highly heterogeneous proppant packings hypothesized to form during channel fracturing. In some cases, these heterogeneous packings show drastic improvements in conductivity with only moderate increase in the stress on the proppant particles, suggesting that in certain applications these structures are indeed optimal. We also compare our computer-generated structures to micro computed tomography imaging of a manually fractured laboratory-scale shale specimen, and find reasonable agreement in the geometric characteristics.

1. Introduction

Hydraulic fracturing (“fracking”) is a highly effective and widely used technique for stimulating production from oil and gas reservoirs, in which high pressure fluids are pumped into wellbores to initiate and expand fractures in the target rock formation. In most applications, after a fracture is generated, a suspension containing proppant particles is injected in order to keep fractures open once the hydraulic pressure is removed. Propped fractures then provide a pathway for rapid transport of hydrocarbons from the rock formation to the wellbore, which in many reservoirs, especially tight shale rocks, is the transport-limiting step. Maintaining high well productivity therefore relies on robustly propped fractures, wherein proppant placement maximizes fracture conductivity, defined as the product of the propped fracture permeability and width. Intuitively one expects a high porosity proppant pack to provide higher fracture conductivity; however, high porosity in the proppant pack also leads to mechanical failure of the proppant, and closure of the fracture. Significant efforts have therefore been made to design proppants and proppant placement strategies aimed at maximizing both of these competing objectives.

Desirable proppants typically have high mechanical strength and ductility (e.g. quartz sand, aluminum,[1] reinforced resin pellets[2] or bauxite[3]) and particle properties that yield a relatively high pack porosity (e.g. smooth spherical shapes, with minimal dispersion in particle size,[4] or even rod-like particles.[5]) In addition to the selection of the proppant material and particle characteristics, placement of proppant in the fracture can have a significant influence on the resulting conductivity. Conventional wisdom dictates that a given proppant will result in a particle pack with a fixed permeability, and the primary way to increase fracture conductivity is to increase the fracture aperture. This in turn implies the existence of multiple proppant layers across the fracture aperture (see Fig. 1a). Early work by Darin and Huitt[6] challenged this notion, and proposed the placement of proppant in ‘partial monolayers’ (see Fig. 1b), which could provide exceptionally high porosity and ample flow paths through the proppant pack, while minimizing the quantity of proppant needed. While initially considered

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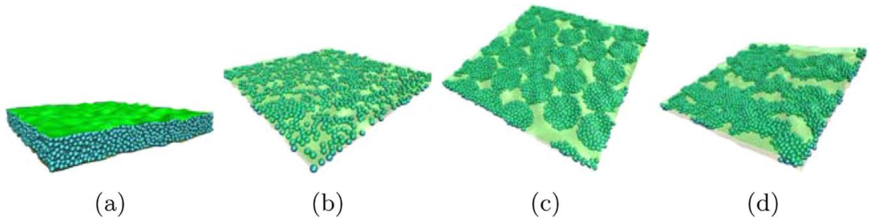

Fig. 1. Examples of different types of proppant packs. (a) Homogeneous, multi-layered close packing. (b) Partial monolayers. (c) and (d) Heterogeneous pillar and finger-like structures (resembling those resulting from channel fracturing techniques[8,9]).

impractical due to difficulties in achieving such structures and the instability of the resulting fracture (e.g. closure due to proppant embedment or crushing), subsequent work suggests that this may indeed be feasible.[7] More recently, proppant injection methods have been developed that achieve highly heterogeneous proppant placement, which can lead to drastic improvements in fracture conductivity. The most notable among these are channel fracturing techniques, which involve alternating pulses of proppant-loaded and proppant-free fluid as well as addition of fibrous material,[8–10] resulting in the formation of pillar-like proppant structures separated by open flow channels (see Fig. 1c). Other heterogeneous proppant structures have been observed using reverse hybrid fracturing techniques, which involve the use of fracture fluids with highly disparate viscosities and proppant loadings (see Fig. 1d).[11] We refer to conventional proppant placements, where particles are close-packed in multiple layers or monolayers, as homogeneous packings; in contrast, non-traditional proppant structures such as those resulting from channel fracturing will be referred to as heterogeneous packings.

Advancements in hydraulic fracturing technologies will likely enable additional varieties of heterogeneous proppant pack structures. These have been shown to be effective at increasing fracture conductivity in laboratory-scale experiments as well as field tests.[7,11,8] Such results provide useful overall measures of fracture quality, either as direct measures of conductivity (as in laboratory-scale experiments) or in the form of overall well production. However, these measures convolute several important fundamental features of the propped fracture. In field tests especially, the details of proppant placement are nearly always unknown and therefore the structural characteristics of the proppant pack cannot be conclusively related to changes in fracture conductivity and well productivity. In laboratory-scale experiments, the mechanical loading of the proppant pack is typically only assessed based on total confining pressure, which may not be predictive of long-term or field stability.

We therefore undertake a simulation-based approach, which allows us to computationally construct a broad range of proppant pack geometries and investigate them in detail with respect to conductivity and mechanical loading characteristics. A key simplification of our approach is that we do not attempt to simulate the proppant injection and fracture generation process. Instead, we use simplified simulations only to generate static proppant pack structures; rather than concerning ourselves with how these structures can be created or how they evolve, we focus exclusively on characterizing their hydraulic and mechanical properties. Nevertheless, our proppant pack generation simulations contain sufficient detail to produce realistic proppant structures that capture the key features of the most commonly hypothesized structures. Comparison with experimental data in the literature as well as in our own work suggests that these structures are indeed realistic and achievable.

Our simulations are based on an explicit particle-scale representation, which is essential for accurate characterization in cases where the fracture aperture is comparable to the particle size, and for heterogeneous particle packings in general. Using discrete element method (DEM) simulations, we first construct various proppant pack geometries, then compute fracture conductivities using finite element method (FEM) simulations of flow through the resulting geometries. The stress state of the particle packs is assessed based on forces computed in the DEM simulations. This work is conceptually distinct from most applications of DEM to hydraulic fracturing, which use bonded particle models to study mechanics and fracture of the rock formation[12–14]; instead, we use DEM simulations only to represent proppant particles and artificially generate proppant-packed fractures, without addressing the detailed mechanics of the surrounding rock formation. A combination of these approaches, where both the proppant pack structure and the mechanics of the rock formation were studied using DEM, was recently presented by Deng et al.[15] However, their focus was on the mechanics of the rock formation for various particle types and pressures, and they only considered homogeneous, multilayered packings.

Studies in a similar vein to the present work include the work of Khanna et al.,[16] who used FEM simulations to study permeability in a proppant monolayer consisting of regularly spaced particles with various degrees of embedment. While the flow analysis is in principle similar, we explore a wider range of proppant structures, including multilayered close packings, monolayers and other heterogeneous packings, and additionally investigate the stress state of the proppant packs. Experimentally, Thompson and coworkers have advanced the use of X-ray microtomography to obtain three-dimensional representations of laboratory-scale homogeneous particle packs.[17–19] Flow simulations at various stress conditions have been carried out based on the resulting geometries.[20–22] The simulations that we present here complement such work with a much broader range of simulation-generated proppant packings, and we hope will guide experimental investigations of additional packings and proppant types of interest, as well as motivate more detailed experimental measurements of particle pack stress states.

2. Methods

2.1. Discrete element method simulations for generating proppant packs

Realistic proppant injection processes involve a series of complex highly-coupled physical phenomena, including fracture initiation and propagation, time-dependent suspension flow (usually including viscoelastic effects), and large deformation/fragmentation of proppant particles and the surrounding rock formation. Accurately capturing all of these physics to model proppant injection at the particle scale is not currently computationally feasible; we therefore use simplified particle simulations only to generate proppant packings of interest. We focus on the final (idealized) proppant pack structures for purposes of comparison among different proppant placement strategies, rather than an accurate model of the injection process or high fidelity between the resulting computational geometries and laboratory or field tests. However, we also show that our computer-generated structures are qualitatively similar to experimentally generated proppant packings.

Discrete element method (DEM) simulations have been used extensively to study particulate matter.[23] Here the discrete elements represent individual proppant particles, and the rock formation is modeled using rigid boundaries (walls). For simplicity, all proppant particles are assumed to be spheres, which is desirable for a large number of proppants in common use; however, our simulations could readily be extended to non-spherical particle types, e.g. using a clustered overlapping sphere approach.[24] We model particle-particle and particle-wall interactions using a standard Hertzian spring-dashpot model with a shear history-dependent Coulomb friction criterion. For