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Research Paper

Grain breakage criteria for discrete element models of sand crushing under one-dimensional compression

Wenbo Zheng*, Dwayne D. Tannant

School of Engineering, University of British Columbia, Kelowna, BC V1V 1V7, Canada

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ABSTRACT

Frac sand consisting of quartz grains is widely used in hydraulic fracturing of tight shales to prop fractures open. However, the sand can be crushed by high compressive stress acting on the fractures and this reduces the fracture conductivity. In practice, a one-dimensional compression test is widely used to evaluate the crushing resistance of frac sand. This paper presents the results of discrete element modelling of sand crushing calibrated with laboratory data from one-dimensional compression tests. Three criteria for grain breakage that incorporate grain-size dependent particle strength and failure under shearing/tensile conditions were implemented and evaluated in PFC^{2D}. An innovative aspect is linking the breakage of a clustered particle under multiple contacts in PFC^{2D} to grain breakage criteria to examine the applicability of these breakage criteria in grain crushing. A macro-scale calibration demonstrates how incorporation of particle breakage algorithms can allow the PFC^{2D} model to capture the change in particle size distribution as well as the non-linear stress-strain response of sand under high compressive stresses. The calibrated grain breakage criterion was used to study the crushing behaviour and permeability evolution of a mesh 20/40 Jordan frac sand.

1. Introduction

Frac sand is widely used as a proppant for hydraulic fracturing to increase the recovery rate of hydrocarbons in the oil and gas industry. After hydraulic fracturing, a sand pack is formed between fractures to resist the closure stress and prop open fractures, which act as paths for oil and gas to flow. However, the high closure stress within the hydraulic fractures often crushes sand grains into smaller fragments [1]. Sand crushing reduces the fracture aperture and the void ratio of the sand pack. The presence of small fragments of crushed sand greatly decreases the permeability by blocking hydrocarbon flow paths [2]. In current practice for frac sand selection, the ISO 13503-5 standard uses a conductivity cell with proppant grains embedded between two fracture faces to measure fracture conductivity [3]. For different formations under different closure stress, many tests are needed to select an optimal proppant, which is very time-consuming and requires large specialized testing equipment. Another standard (ISO 13503-2) uses a one-dimensional compression test to measure the percent of fines (smaller fragments of grains) generated due to crushing under a specific stress [4,5], which can be further linked to estimates of sand pack permeability using empirical equations [6]. Alternatively, the sand pack conductivity can be predicted from numerical simulations. However, most models developed for sand pack permeability estimation only represent sand pack compaction with Terzaghi's soil consolidation theory [7,8] or the Mohr-Coulomb constitutive model [9] and do not consider proppant crushing that alters the grain size distribution and stress-strain response. The motivation of this study is to develop numerical models to both capture the change of the grain size distribution and stress-strain response during the grain breakage process [10].

The discrete element method (DEM) has been widely used to simulate the grain breakage and comminution processes under static compression [11–13]. In DEM, there are two approaches to simulate grain breakage. The first approach is to represent each grain with a cluster of many smaller particles, and grain breakage is modelled as contact bond breakage within the cluster of particles [14–16]. The second approach is to represent each grain with a single particle in the DEM model. A breakage criterion is used to determine whether a particle breaks [17–19]. A breakage criterion is a measure of a stress index within the particle that can be related to the particle strength obtained from experiments. When the stress acting on a particle exceeds the particle strength, the particle is replaced with smaller particles to mimic fragmentation. Due to the higher computational effort of the first method, the second approach has been widely used to simulate the crushing of sand grains. McDowell and De Bono [20] discussed the influence of different particle splitting approaches and particle strength distributions on the void ratio-compressive stress as well as grain size

* Corresponding author.
E-mail addresses: wbzheng@alumni.ubc.ca (W. Zheng), dwayne.tannant@ubc.ca (D.D. Tannant).

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distributions. De Bono and McDowell [21] gave a comprehensive comparison of several crushing criteria using different crushing stress indexes. They found that criteria that use the maximum contact forces and octahedral shear stress match with the experimental responses.

In spite of numerous DEM studies on grain breakage under compression, most studies have focused on exploring the effect of micro-parameters on macro-scale behaviours such as normal compression lines and critical state lines or micro-scale responses such as evolution of contact numbers and contact forces [22]. The calibration of the DEM for grain crushing with a breakage model has rarely been reported to our knowledge. Belheine et al. [23] calibrated micromechanical properties of DEM particles to match triaxial stress-strain response of Labenne sand but grain breakage was not considered. Behraftar et al. [24] used dimensional analysis to calibrate the micro-parameters of bonded DEM elements against the laboratory data of cracked chevron notch Brazilian discs, which can be classified into the first approach to simulate grain breakage and is computational expensive when many particles are present. This paper attempts to calibrate the existing crushing criteria with laboratory data from one-dimensional compression tests on Jordan Formation frac sand. This frac sand is widely used for hydraulic fracturing. One innovative aspect of this paper is the first published exploration of the validity of three different crushing indexes from a micro-scale approach using clustered balls to simulate grain breakage. Then a macro-scale calibration of the crushing criteria was performed to obtain the strength parameters for Jordan Formation frac sand by matching both the laboratory grain size distribution and the stress-strain response. Finally, a calibrated criterion with calibrated particle strength for Jordan Formation sand was used to study the crushing behaviour of the sand and to predict sand pack permeability reduction within a hydraulic fracture caused by high closure stresses.

2. One-dimensional compression lab tests

A one-dimensional compression test was used to investigate the Jordan Formation frac sand crushing resistance. This test involved placing sand into a steel cup with a 25.4 mm inner diameter and then applying a compressive stress to the top of the sand with a steel loading piston as seen in Fig. 1. An Instron 3385H testing machine was used to apply a vertical compression force to the piston. For each crushing test, 10 ± 0.1 g of sand was placed into the cup. The height of the sand in the steel cup was measured before starting each test. The tests at each stress level were repeated five times to evaluate the inherent variability in the test data and to obtain a sufficient mass of sand for subsequent sieving. The sand grains from each set of five tests were combined together, and a sieve analysis was performed to determine the grain size distribution following the ASTM D6913 sieving standard [25].

After a test, the piston was removed from the cup and the sand grains inside the cup were observed with a microscope. Fig. 2 shows a typical example of crushed sand as seen by the white coloured particles in the cup. A diametrical failure in which a round grain splits into two halves is shown at location 1. The split grains were further broken into many pieces of finer fragments as shown at location 2.

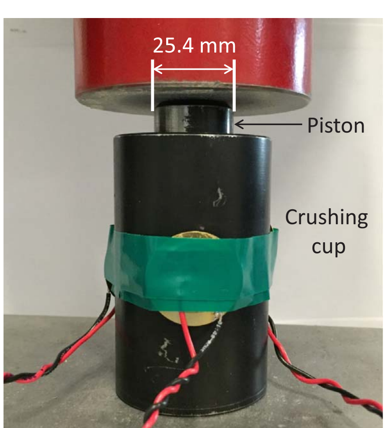

Fig. 1. Steel cup and piston used for a one-dimensional compression test.

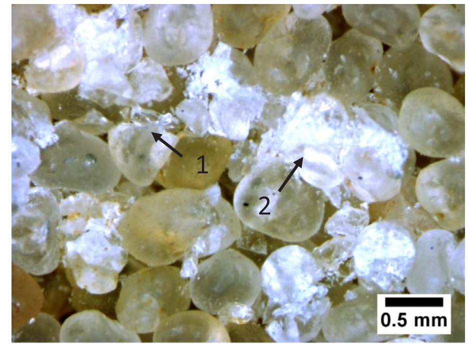

Fig. 2. Crushed and intact sand grains after 40 MPa compression.

G600 sand collected on a 600 μm sieve (passing 710 μm sieve) was used in the one-dimensional compression tests. The sand was compressed to stresses of 30 and 40 MPa. The grain size distribution after reaching each stress level was measured by sieve analysis. The sand crushing percentage is defined as the percentage of grains retained on the finer sieves (e.g. grains passing a 600 μm sieve for G600 sand). The crushing percentage is 13.8% and 29.2% respectively for stresses of 30 and 40 MPa. As expected, a higher percentage of sand is crushed when the stress increases.

The stress-strain response of the sand pack was recorded during the crush tests as shown in Fig. 3. Stress drops in the stress-strain curve are observed, which were caused by grains breaking within the cup [6]. The gradient of the stress-strain curve decreases when the compressive stress exceeds 25 MPa showing that with further increase of compressive stress, the G600 sand behaves less stiff.

3. DEM modelling of one-dimensional compression test

3.1. Modelling without grain breakage

A discrete element tool PFC^{2D} [26] was used to simulate the sand compaction in a one-dimensional test without considering grain breaking. A uniform distribution of particle sizes between 710 μm and 600 μm was used to create a particle assembly in PFC^{2D} to represent G600 sand. The particles were generated in a predefined space above the cup and then dropped to the cup under gravity. A linear contact model was used and the micro parameters were based on those used by

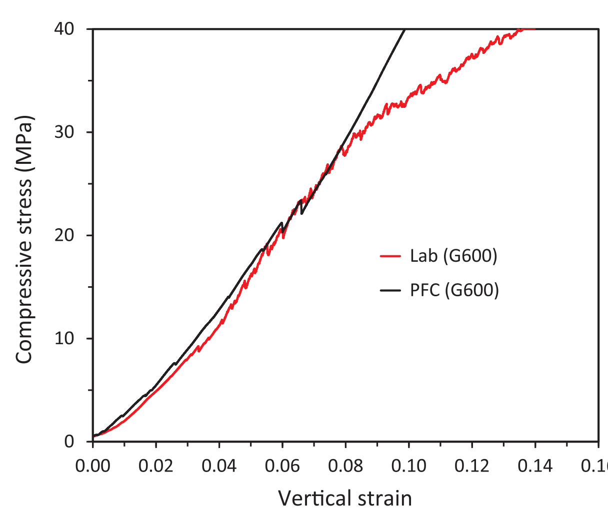

Fig. 3. Stress-strain response of G600 sand compressed up to 40 MPa.