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# Micromechanical investigation of fines liberation and transport during coal seam dewatering

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## ABSTRACT

The reduction of subsurface hydrostatic pressure to allow natural gas desorption is an integral step in the production of coal seam gas (CSG). During this dewatering stage, viscous stresses can cause the liberation and transport of fines, which are predominantly comprised of inorganic clay groups such as smectite, illite and kaolin, from within the coal matrix. Dislodged particles migrate in production fluid through fractures towards the wellbore where capture and deposition can deteriorate the reservoir's permeability. Once in the wellbore, these particles can adversely affect the performance of mechanical equipment such as pumps. This study uses direct numerical simulation of a synthetic coal fracture to help elucidate the particle detachment process. This is approached using a coupled lattice Boltzmann-discrete element method to capture both physical and physicochemical interactions based on Derjaguin-Landau-Verwey-Overbeek (DLVO) theory. Preliminary testing with the developed model suggests that particles move almost freely along the bounding surface regardless of electrostatic interactions, and that Hele-Shaw predictions of particle lift in particular can be inadequate. Further, larger-scale simulations indicated that the DLVO parameters can significantly impact the vertical position of propagating fines with variations in eroded mass of over 100% observed for the range of tested salinity levels.

## 1. Introduction

In the production of coal seam gas (CSG) a common phenomenon causing reduced gas extraction and damage to upstream equipment is the detachment and migration of fine particles from within the coal seam. These particles have been observed in laboratory and field tests to have the potential to reduce coal seam permeability and induce what is referred to as formation damage. The transport of solids to the surface can also cause premature failure of pumps and piping equipment, leading to excessive wear and loss of containment in extreme cases. The processes by which fines are detached is yet to be fully understood (Bradford and Torkzaban, 2008) and mitigation tactics are yet to be proven completely effective. This investigation aims to numerically model the detachment process in order to further develop an understanding of the migration phenomenon.

In order to extract CSG, drilling operations are performed which allow ground water to be pumped to the surface. It is during this dewatering stage that particle detachment and transport towards the wellbore is investigated. Fine particles, herein referred to as fines, are defined in this study as clay particles able to be suspended in production fluid, and have sizes on the order of micrometers. Whilst research into the phenomenon of particle detachment and migration in CSG exists, the majority of these studies tend to be limited to continuum models in which concentration levels of suspended particles are tracked through advective-diffusive transport equations (Bradford et al., 2003; Bedrikovetsky et al., 2011; Zeinijahromi et al., 2012). In comparison, this study will focus on the grain-scale interactions that result in particle liberation.

The permeability of coal is an important parameter when considering CSG extraction. The transportation of methane

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towards the surface involves two stages. It first diffuses from the coal matrix before flowing through macropores in the coal seam towards a wellbore. The macropores include the network of face and butt cleats, bedding planes, and any other natural or induced fractures. In the most straightforward scenario the bedding planes are oriented perpendicular to gravity, however this can change post-deposition due to large-scale strata movement (e.g. faulting, folding). The face cleats are then typically parallel to the bedding planes and the butt cleats orthogonal to both. For the most part, it is these fractures that facilitate extraction which is economically feasible. Therefore, when these flow channels reduce in size and or become blocked production is often adversely affected.

When discussing the migration of fines in this report, reference is being given to the entire sequence of occurrences that determine their trajectory through the reservoir as well as their final capture or extraction. This includes foremost the detachment and or release behaviour of fines from the porous matrix. Khilar and Fogler (1998) reported the detachment of fines to be a result of colloidal interaction (both with the surface and additional migratory fines) and hydrodynamic forces, which are directly simulated in this investigation.

This paper presents a numerical framework for the simulation of grain-scale interactions that act to detach and transport fines within a coal seam. The developed computational model employs the lattice Boltzmann method (LBM) to replicate fluid flow coupled with the discrete element method (DEM) to track the behaviour of fines. Section 2 briefly reviews the physicochemical forces that act on fines along with empirical models for detachment kinetics. The direct numerical simulation (DNS) approach employed in this study is presented in Section 3, including the DEM for particle mechanics, the LBM for fluid mechanics, and the implementation, validation and verification of physicochemical particle forces. Section 4 summarises the results of small-scale simulations that investigate the liberation and transport of fines and, finally, Section 5 offers some concluding remarks.

## 2. Modelling of fines as colloids

In this study, fines are modelled as spherical colloidal particles. In doing this, the charge and average size of each particle can be defined in order to analyse its behaviour under varying subsurface environmental conditions. Thus, as particles are detached from the coal matrix a particle suspension problem is formed. This can have an impact on the rheology of the fluid in the system, and as such an understanding of how detachment occurs is necessary.

### 2.1. Colloidal interactions

Colloid mobilisation and immobilisation can often be thought of as the result of two types of perturbations. Namely, there are physical forces imparted on suspended and attached particles by the aqueous phase. While suspended, particles can be accelerated towards the surface of the coal matrix leading to capture of the particle or detachment of additional fines. Whereas, for attached particles, the fluid imparts both drag and lift which act to mobilise the colloid into the solution. Additionally, the physicochemical interactions that take place during colloid-colloid and colloid-surface perturbations can have a strong impact on particle behaviour (Ryan and Elimelech, 1995). This involves attractive and repulsive electrostatic forces between solid interfaces. In this investigation, these forces are taken according to Derjaguin-Landan-Verwey-Overbeek (DLVO) theory, which summarises colloidal interactions as the superposition of London-van der Waals and electric double layer (EDL) energies.

#### 2.1.1. DLVO theory

The expressions for drag, lift and gravity forces on a solid spherical particle in a fluid are quite common in the literature. It is when investigating the electrostatic interactions between particles that are separated by distances on the order of nanometers that a complete understanding is lacking (Liang et al., 2007). Classical DLVO theory takes the assumption that interaction forces between solid surfaces in a liquid can be taken as a superposition of London-van der Waals attraction energy and the double layer electric effect (Liang et al., 2007).

Since first proposed in the 1940s, DLVO theory has been subject to considerable experimental testing, showing both strengths and weaknesses (Daintith, 2008). A primary weaknesses is that of describing colloidal behaviour in an aggregated state, at which short-range interactions (surface separations of the order of 1 *nm*) such as the Born potential become important due to the specific properties of ions. When formulating a DEM simulation for the detachment scenario, these interactions are neglected due to the time-scale requirements needed to capture stable behaviour at this resolution. As a result, a *cut-off* distance on the order of $10^{-8}$ *m* or 1% of particle radii is defined in line with a smooth geometry assumption. Using this cut-off distance tends to create a primary energy minimum at the point of particle contact causing captured particles to have no surface separation distance.

#### 2.1.2. London-van der Waals attraction

It was noted by Hamaker (1937) that the apparent adhesion forces between small particles of any substance or a particle and a surface was a common occurrence in colloidal systems with processes such as flocculation being the most striking example. The attractive force originates due to dipoles of atoms interacting between colloids over finite distances. This relatively weak interaction energy becomes significant when integrated over solid bodies at the microscale and can dominate their behaviour. The works of Bedrikovetsky et al. (2011) and Khilar and Fogler (1998) perform this integration using the comparison of a sphere to a flat plate under the philosophy that, relative to a colloid, the surface is similar to a particle with infinite radius. Under this assumption, the London-van der Waals energy potential is given by Equation (1) [1] and is a function of the ratio of the minimum surface separation to the diameter of the particles, *x*. The other parameters of importance include the ratio of interacting particle diameters, *y*, and the Hamaker constant, $A_{132}$, which are determined by the system environment.

$$V_{LvdW} = -A_{132}\frac{1}{12}\left(\frac{y}{x^2+xy+x}+\frac{y}{x^2+xy+x+y}\right.\\\left.+2ln\frac{x^2+xy+x}{x^2+xy+x+y}\right) \tag{1}$$

In order to formulate a flat plate to sphere relation, the value of *y* is taken to infinity (Hamaker, 1937), giving,

$$V_{LvdW} = -A_{132}\frac{1}{12}\left(\frac{1}{x}+\frac{1}{x+1}+2ln\frac{x}{x+1}\right), \quad y\to\infty. \tag{2}$$

If one then takes $Z=\frac{x}{2}$, equivalently the ratio of surface separation to particle radius one obtains the expression used by Bedrikovetsky et al. (2011),

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[1] Full details of surface integration to obtain energy terms can be found in Hamaker (1937).