Modeling sand production with Darcy-Flow coupled with discrete elements

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ABSTRACT: The discrete element method has been in development for several years. As the method matures, it is being extended and applied to a wider range of applications. As our computational capacity increases, the complexity of the phenomena that are being modeled also increases. The move toward more accurately modeling the physics of the problem is requiring the coupling of different numerical techniques. Coupled physical processes are commonly found in the petroleum industry, in particular, coupling between solids and fluids. One such problem is the occurrence of sand production in oil wells. As a result of the in situ stresses and fluid flow, poorly consolidated sandstone in some formations tend to disaggregate. This is a costly problem that is mitigated by very conservative approaches. This paper explores the coupling of 2-D DEM and a finite element implementation of the 2-D Laplace formulation for Darcy-Flow as a technique for assessing the potential for sand production.

1 INTRODUCTION

Sand production in oil wells is a costly and prevalent phenomenon that is not well understood. Sand production is the disaggregation of the formation due to a combination of in-situ stresses and fluid flow. It tends to be a progressive process once started and, as a result, the oil companies tend to take a conservative approach to the use of preventative measures such as gravel-pack filters or screens down-hole. Sometimes this equipment is unnecessarily installed as a preventative measure, increasing the cost of production and decreasing the productivity of the well. At the present time, the prediction of sand production is empirically based. A better understanding of the root cause of sand production is necessary to improve the prediction of the production zones and wells that are susceptible to sand production. As is often the case with micromechanical processes, it is difficult to be a neutral observer when experimentally investigating the causes of sand production. Numerical tools can provide insights and qualitative measurements that cannot be obtained experimentally.

In order to better investigate such micromechanical processes, a discrete element method (DEM) code MIMES has been developed. (Rege et al 1996) By coupling MIMES with Darcy fluid flow, this DEM code can be used as a means to study the phenomena that drive sand production as well as other coupled fluid-flow/particle motion processes.

2 DISCRETE ELEMENT METHOD (DEM)

The granular material application of DEM was originally developed about twenty years ago. (Cundall et al 1979) The basic idea of DEM, and as it is implemented in MIMES, is straightforward. Particles are modeled as independent, unique objects. These objects come into contact with neighboring particles. The interaction of these particles is modeled as shown in Figure 1 with a spring and dashpot in the normal direction and a spring, dashpot, and frictional slider in the tangential direction. Forces of each contact are computed based on the distance of particle overlap and the magnitude of the spring stiffness. When the tangential contact force reaches a predetermined limit, which can be related to the normal force, such as Coulomb friction, sliding occurs, thereby modeling interparticle friction. The interparticle contact relationship is based upon a simple linear-elastic constitutive model with option of other more sophisticated contact models, such as a nonlinear Hertzian contact model. The resultant contact force acting on the particle is computed and the ac-

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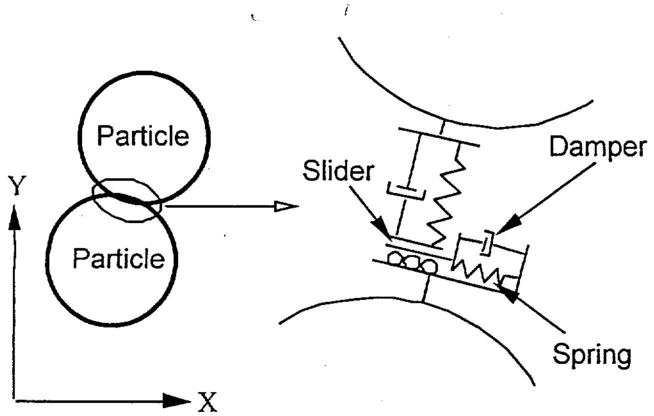

Figure 1. Particle contact model as idealized in DEM.

celeration of the particle is found using Newton's law. Using explicit time integration, the new velocity and displacement of the particle is calculated. From this new position, new contacts and contact forces are found, restarting the cycle.

In most implementations of DEM, particle-shape is a simple disc or sphere due to the fact that very robust, fast contact detection schemes require this simple geometry. However, several researchers have found that particle shape has a distinct influence on the response of the particles. (Jensen et al and Ting et al 1993) Spherical and disc shaped particles cannot capture the inherent geometry-dependent behavior that asperities, particle angularities, and particle roughness imparts. In order to capture some of these effects, the basic shape used by MIMES is an n-sided polygon. For ease of input of a wide variety of shapes, the superquadric equation is used as a template to define the particle boundaries. (Williams et al 1992)

3 FLUID-FLOW IMPLEMENTATION

3.1 *Darcy finite element formulation*

In MIMES, fluid flow simulation is accomplished by using finite element techniques to solve the 2-D Laplace formulation for Darcy-Flow given in Equation 1. (Klosek 1995)

$$k_x \frac{\partial^2 \phi}{\partial x^2} + k_y \frac{\partial^2 \phi}{\partial y^2} = 0 \qquad (1)$$

where k_x and k_y are porous media permeabilities in the x and y directions and ϕ is the pressure (potential) function, which is the only variable (or degree-of-freedom) in the problem. (Segerlind 1984) The current implementation assumes that k_x and k_y are equal, requiring only one input, k. Two methods for treating the permeability have been incorporated in MIMES. The first assumes that the permeability remains constant throughout the simulation in which case the fluid-flow conditions are solved for only one time. The second method allows the discrete element distribution to modify the permeability. This will be discussed in detail in a later section. In cases where the discrete elements are allowed to modify the permeability, a fluid solution can be obtained at a user-specified frequency, n, which is the number of discrete element time steps between fluid-flow solutions. Fluid pressure integration on each discrete element is based on pressure gradient and is described by Preece et al. (1999)

3.2 *Discrete element distribution effect on permeability*

An important capability of MIMES is Darcy flow permeability modification based on location of the discrete elements relative to the fluid flow mesh, thus completing the coupling between fluid-flow and discrete element movement. The porosity of the discrete elements can be easily calculated and can be related to the fluid-flow finite element based on the coverage of the element by discrete particles. The porosity is then related to permeability (Das 1990 and Holtz et al 1981) as given in Equation 2 below,

$$k = C\frac{e^3}{1+e} \qquad (2)$$

where k is the permeability, C is a constant, dependent on the material from which the porosity is created, and e is the porosity of the medium. Currently, the porosity of each triangular finite element is determined by intersecting the bounding circle for the discrete element with the triangle. The bounding circle approach causes some problems if the discrete elements have significant aspect ratio causing the bounding circle to affect the porosity of adjacent finite elements that it does not cover.

4 SAND PRODUCTION SIMULATION

A series of three coupled fluid-flow/particle-motion simulations of sand production from an oil well perforation channel were performed. All of the simulations had the same initial conditions except the magnitude of the tensile bonds, which represents the cohesive strength of the particle assembly. The simulation is of the cross-section of the perforation channel. Figure 2 shows the initial state of the packed particles, the boundary particles, and the fluid mesh. The perforation channel where freed sand particles are drawn away from the formation into the borehole is modeled by a sink particle. As a particle comes in contact with the sink particle, it is eliminated from the simulation, thereby modeling the

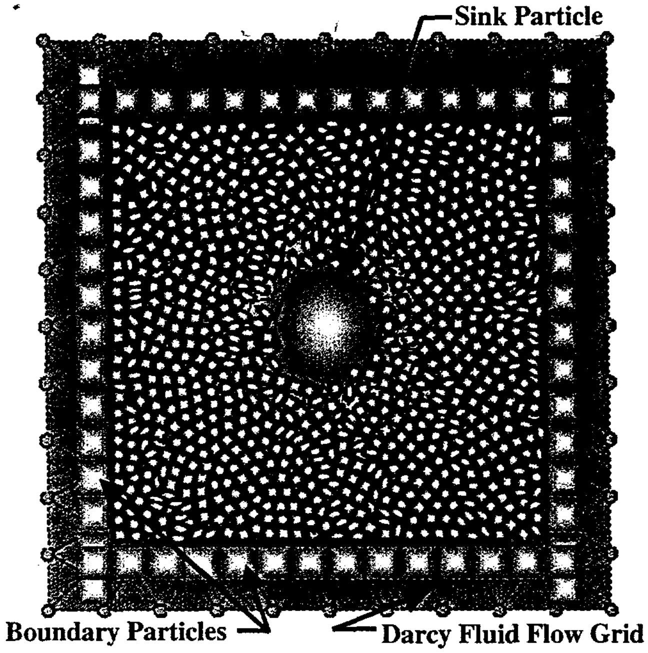

Figure 2. Geometry of perforation channel illustrating the fluid flow mesh, boundary particles, and sink particle. The sink particle represents a perforation channel. A constant force is applied to the boundary particles in order to simulate in situ stresses. Initial state of packed particles under in situ stress. The particles are bonded with tensile bonds at all contact points.

eliminated from the simulation, thereby modeling the perforation. Applying a constant force to the boundary elements, which move as a rigid body, simulates an in situ stress since the simulation is 2-D. The particles are bonded with a tensile bond at all contact points. The means of bonding the particles in DEM is detailed by O'Connor et al. (1997) The fluid-flow solution was assumed to be steady state and was calculated only at the initial time step. Therefore the capability for particle-modified permeability was not utilized. This improvement will be added in future simulations. The cohesive strengths used in the different simulations are 1000 N, 1700 N, and 3000 N, for simulations A, B, and C, respectively.

Figure 3 shows simulation B in a steady state. At this point it can be seen that some of the particles have broken off from the matrix, but the formation is still stable. Simulation C, which had the highest level of particle-to-particle cohesion, was similar to B but with fewer particles broken from the matrix. In simulation A, which had the weakest level of particle-to-particle cohesion, the formation collapsed and all of the particles moved to the center of the simulation and were eliminated from the simulation, which is analogous to being drawn to the borehole through the perforation. The simulations showed that as the value of the point-to-point cohesion decreases, the number of particles breaking from the matrix increases. This follows the same trend as is found in production wells in more poorly consolidated sandstone where problems with sand production tend to exist. This strengthens the assumption that sand production occurs in more poorly consolidated sandstone due in part to weaker particle bonding.

5 CONCLUSION

This paper discusses the successful coupling of fluid-flow with a DEM system using a Darcy fluid-flow formulation implemented into the DEM code MIMES. A series of simulations were discussed which demonstrate the ability of the coupled fluid-flow/particle-motion capability of MIMES to analyze complex problems such as sand production. In these simulations, it was seen that as the strength of the cohesive bonds decreased, the number of particles breaking free from the matrix increased. These simulations seem to indicate that fluid-flow coupling with DEM can be used as a tool to increase the understanding of the mechanisms that cause sand production.

While the results were encouraging, some deficiencies remain. Because deleterious boundary effects could influence the solution, a much larger number of particles need to be used in the simulations. It could also be argued that Darcy fluid flow is not the best description of the physics where particles are being transported by the fluid. Furthermore, two-dimensional analyses in a three-dimensional world are always plagued by questions of applicability. Particle behavior can be quite different when the motions are not constrained to movement within

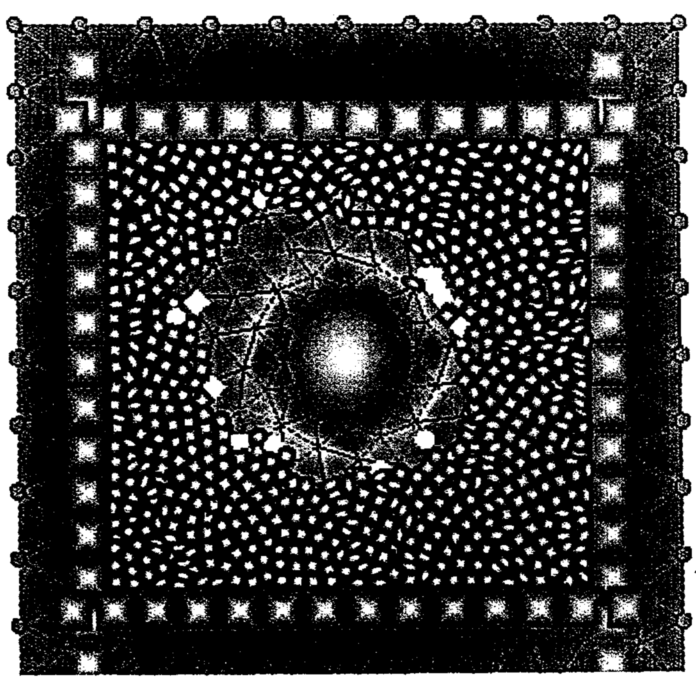

Figure 3. Simulation B. Point-to-point particle cohesion is 1700 N. The simulation is at a steady state. Note the loss

plane. Porosity and permeability are also difficult to define in two dimensions.

In order to address some of these issues, present and future work include parallelization of the code, a Lattice-Boltzmann implementation of the fluid flow, and extension of the code into 3-D.

6 ACKNOWLEDGEMENTS

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http://wwwdinma.univ.trieste.it/~nirftc/research/easymesh

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