Advanced Simulation Technology for Combined Percussion and Rotary Drilling and Cuttings Transport

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Basic research is required to advance simulation technology and help industry more economically recover vast untapped gas resources contained in deep, hard rock environments.

Development of more efficient and lower cost drilling technology will significantly increase gas production by allowing economic exploitation of difficult formations, such as deep, hard rock reservoirs. The estimated yearly cost to drill hard rock in the United States exceeds $1 billion. Potential savings of $200 million to $600 million are possible if the penetration rate in hard rock can be doubled while maintaining bit life, according to Tibbitts et al.

There is evidence the combination of percussion and rotary drilling techniques can potentially provide significant improvement in rate of penetration in hard rock environments (see review by Samuel, 1996). In addition to faster penetration, other benefits include the ability to use lower weight on bit, less contact time with rock and therefore less abrasion and longer bit life, improved hole deviation control and generation of larger cuttings allowing improved geologic interpretation. These potential and theoretical advantages for combined percussion and rotary drilling, however, have not been consistently demonstrated in the field.

The fundamental rock mechanics processes associated with combined percussion and rotary drilling have not been fully defined and adequately modeled, and there are no practical simulation tools available to help design and optimize drilling operations. This has led to cost and reliability concerns, limiting the widespread application of percussion
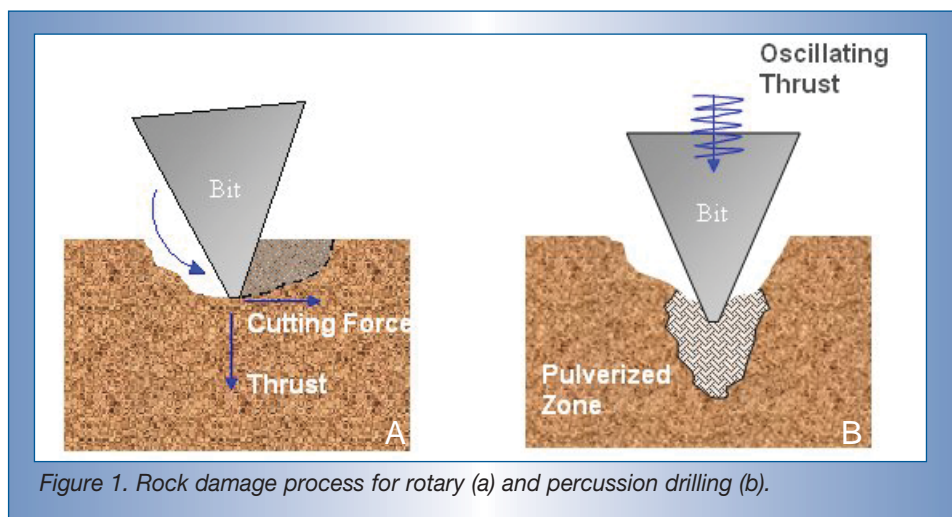

Figure 1. Rock damage process for rotary (a) and percussion drilling (b).

drilling by industry. Terralog Technologies, with partial funding provided by the U.S. Department of Energy, Office of Fossil Energy, National Energy Technology Laboratory (NETL), is pursuing a comprehensive research program to significantly advance fundamental understanding of the physical mechanisms involved in combined percussion and rotary drilling. The project team, headed by Terralog Technologies and supported by TerraTek, has extensive and unique experience and capabilities in fundamental rock mechanics, geomechanical simulation, and full-scale rock mechanics and drilling experiments. The research program includes three primary efforts:

- analytical investigations to develop an improved understanding of the fundamental rock mechanics processes involved in percussion drilling;

- development of advanced simulation technology for the drilling process taking into account coupled structural, particle and fluid flow mechanics; and

- investigation and validation of these improved characterization and modeling approaches with full-scale laboratory experiments.

Background

In rotary drilling (Figure 1a), the bit rotation produces impact and shearing forces. The thrust on drag bits provides a penetrating force normal to the direction of movement that breaks the bond holding the rock particles together. The stress (energy) is built up until relieved by the formation of tension or shear fractures along the direction of thrust. While the impact creates compression, a cutting force perpendicular to the penetrating
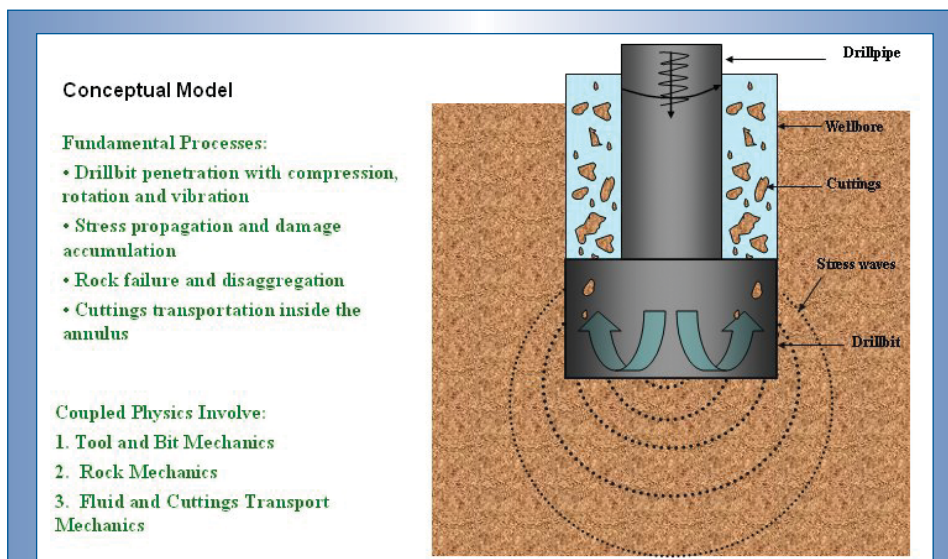
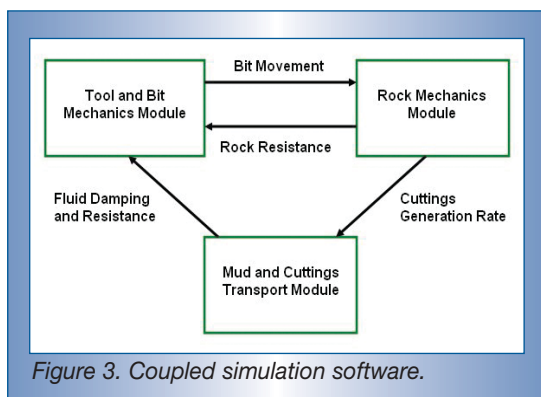Figure 2. Conceptual drilling model and physical processes.

Figure 3. Coupled simulation software.

direction may cause tensile fractures that extend from the bit tip to the rock surface at about 80°. Chip formation occurs discontinuously ahead of the drag bit, and the penetrating and cutting forces oscillate during cutting.

In percussion drilling (Figure 1b), the bit and cutter oscillate axially to impact the rock, imparting compression loads. Developed by the Chinese more than 4,000 years ago, percussion drilling first involved the raising and dropping of heavy piercing tools to cut and loosen earth materials. In 1859 at Titusville, Pa., Col. F. L. Drake completed the first oil well using a cable tool percussion-type machine. One of the earliest reports of percussion drilling technique was documented in 1949. Since then, different terms have been used, such as downhole hammer, percussion hammer, percussive drill

and percussive-rotary drill.

Percussion drilling with and without rotation has been shown to improve rate of penetration in some hard formations, such as siliceous granite, sandstone, limestone and dolomite. In addition to a faster penetration, other benefits include the ability to use lower weight on bit, less contact time with rock and therefore less abrasion and longer bit life, improved hole deviation control and generation of larger cuttings to allow for improved geologic interpretation.

But the potential and theoretical improvements in drilling efficiency using combined percussion and rotary drilling have proved difficult to achieve consistently in the field. The project's objective is to significantly advance the fundamental understanding of the physical mechanisms involved in combined percussion and rotary drilling, and thereby facilitate more efficient and lower cost drilling and exploitation of hard rock reservoirs.

A conceptual model of the drilling process is illustrated in Figure 2. We attempt to better characterize and simulate for fundamental processes during drilling:

- drillbit penetration with compression, rotation and vibration;

- stress propagation and damage accumulation;
- rock failure and disaggregation; and
- cuttings transport away from the bit face and up the wellbore annulus.

These are coupled physical processes, with different physics related to the tool and bit mechanics, rock mechanics, and fluid and cuttings transport mechanics. A coupled simulation system is illustrated schematically in Figure 3. The tool hits the rock face, imparting an impact and shearing load. The rock provides resistance to the tool motion. As the rock becomes damaged and fails, the solid material becomes crushed and disaggregated and adds cuttings to the mudflow stream. The mud system also may influence the tool and bit movement through damping and pressure resistance.

Tool and bit mechanics

The tool and bit motion can be described through the fundamental structural dynamics equations relating force (F) to the combined influences of mass (M) times acceleration (d^2U/dz), damping (C) times velocity (dU/dz) and stiffness (K) times displacement (U).

$$F_z = M_z \, d^2U_z/dz + C_z \, dU_z/dz + K_zU_z \qquad (1)$$

$$F_\theta = M_\theta \, d^2U_\theta/dz + C_\theta \, dU_\theta/dz + K_\theta U_\theta \qquad (2)$$

There is one structural dynamics equation to define the axial motion, with the subscript z shown in equation (1), and one structural dynamics equation to define the rotational motion, with the subscript Θ given in equation (2). In our coupled model simulation process, we solve the equations for a given time increment and impose displacements onto the rock interface.

Rock mechanics

The rock mechanics system (Figure 4) reacts to that imposed deformation during the given time increment. The elements in the rock system deform and may become damaged or fail during that time period, while at the same time, the rock provides resistance to the tool
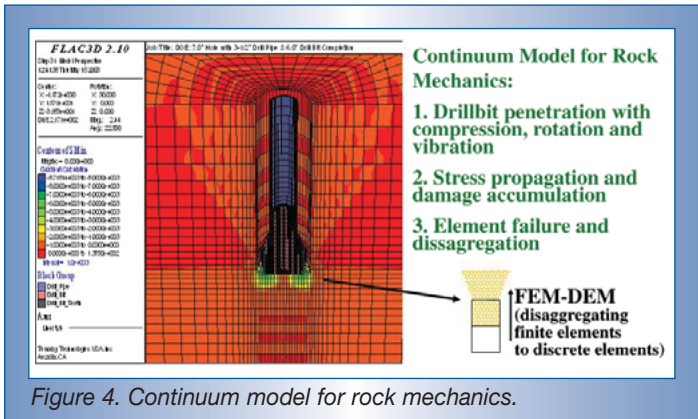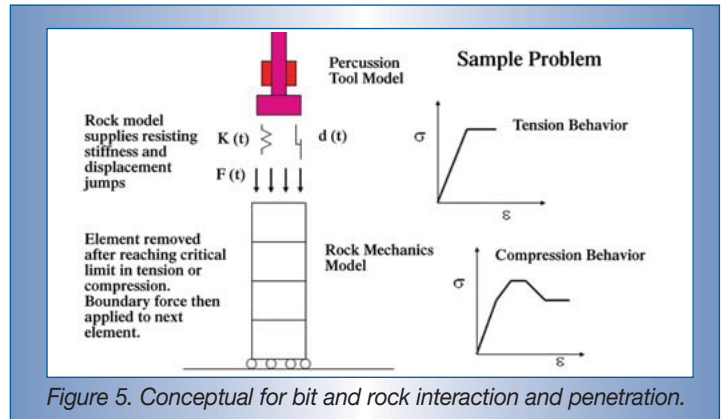
Figure 4. Continuum model for rock mechanics.

Figure 5. Conceptual for bit and rock interaction and penetration.

advance (through a resisting stiffness). In our geomechanical simulation, we apply a continuum model for the rock system, using the FLAC3D software from Itasca.

Stresses and strains are propagated dynamically through the rock based on fundamental continuum mechanics equations. Application of the continuum of the momentum principle yields Cauchy's equation of motion:

$$\sigma_{ij,\,j} + \rho b_i = \rho \; \frac{dv_i}{dt} \qquad (3)$$

where ρ is the mass per unit volume, b is the body force per unit mass, v is rock velocity related to rock displacement (u_i) through $v_i = \frac{du_i}{dt}$, and the subscripts i and j are coordinate system indices. The usual summation convention is implied. The rock total strain increment is a sum of elastic strain increment $\Delta\varepsilon^e$, shear plastic strain increment $\Delta\varepsilon^{ps}$ and tensile plastic strain increment $\Delta\varepsilon^{pt}$:

$$\Delta\varepsilon = \Delta\varepsilon^e + \Delta\varepsilon^{ps} + \Delta\varepsilon^{pt} \qquad (4)$$

Rock is modeled as a Mohr-Coulomb type of elastoplastic material with strain hardening and softening:

$$\vec{f} = f(\sigma_{ij}, \varepsilon_{ij}{}^p, \kappa) \qquad (5)$$

The yield surface (f) where rock starts to behave plastically is defined by dynamic stresses (σ_{ij}) calculated from equation (3), plastic strain ($\varepsilon^p = \Delta\varepsilon^{ps} + \Delta\varepsilon^{pt}$) if the stresses exceed the yield surface and a hardening parameter (κ) that describes rock strength behavior with plastic deformation.

Stresses are related to strains through rock properties, and these change during time as material becomes damaged. When a finite rock element becomes sufficiently damaged so as to lose its inherent strength, it will disaggregate into discrete particles. Generally, this occurs across the entire bit face during a given time interval, and the tool and bit penetrates to the next level of elements.

A conceptual one-dimensional model to illustrate this process is shown in Figure 5. The percussion tool oscillates, rotates and impacts the top of the rock column, which resists the movement by supplying a return stiffness. Rock elements may reach their critical strain limit and fail in tension, compression or shear. The element disintegrates into cuttings and induces a small displacement jump in the tool motion as the bit assembly penetrates deeper into the hole.

Coupled simulation

To simulate cuttings transport mechanics, Terralog has developed a coupled fluid dynamics and particle mechanics model that captures not only macroscopic fluid behavior, but also the effect of solid particles on mudflow and interactions among these particles. A particle suspended in a fluid is subjected to a number of hydrodynamic forces. The momentum of a solid particle moving with a fluid can be described as:

$$\rho_p V_p \frac{d\vec{v}_p}{dt} = -\rho_{fl} V_p g + \int_S T \cdot \vec{n}\,dS \qquad (6)$$

where V_p is particle volume, ρ_p is its density, $\vec{v}_p$ is the particle velocity vector, and T, repre-
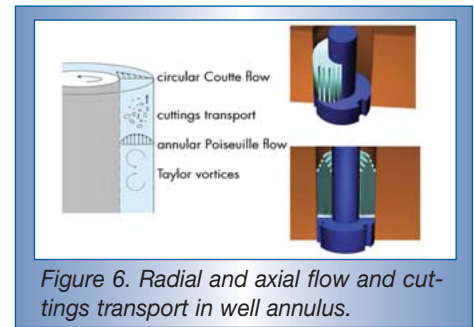

Figure 6. Radial and axial flow and cuttings transport in well annulus.

senting all forces between fluid and particle, is the instantaneous stress tensor that must satisfy the Navier-Stokes equations. A set of constitutive models are developed to calculate various forces from fluid-particle interactions, such as drag forces because of fluid viscosity and pressure difference across a particle, buoyancy forces and particle collisions. The influence of pipe rotation on fluid transportation is considered through a solution of the circumferential velocity for the Taylor Couette experiment. Analytical solutions are available for laminar, Newtonian flow (with patterns shown in Figure 6), while numerical solutions with the help of computational fluid dynamics solvers are required for turbulent and non-Newtonian flow conditions.

Particles generated through rock damage are modeled as individual spheres or clumps of particles to simulate irregular blocks and plates. They are introduced into the drillbit slots and then flow along the annulus. Figures 7 and 8 illustrate two sample simulations showing cuttings transport in vertical and horizontal wells for varying bit penetration and mudflow conditions.

Cuttings transport mechanics

The combined models defining the tool and bit mechanics, the rock mechanics and the cuttings transport mechanics are coupled to simulate the complete drilling process.

First, the tool model generates an impact velocity applied to the rock model. The rock model then calculates loading stresses and determines whether rock failure occurs, and if so, how much. The rock properties, including rock stiffness resisting further bit penetration, are then updated based on damage accumulations. The bit model recalculates bit velocity, which is in turn used by the rock model again. This cycle continues until bit velocity is reduced to zero, which indicates the beginning of bit retreat after impact.

The rock model calculates how much volume of rock will fail based on the implemented failure criteria. This will trigger the cuttings transport model to discretize the failed rock into a number of spheres or clumps, which influences fluid viscosity and therefore its velocity, and which also loads the fluid system with additional cuttings particles. Simulations from the cuttings model are used to determine whether failed rock can be efficiently carried away from the bit-rock impact surface.

Efforts and discussion

The next phase of this project will include laboratory testing and validation studies. We will first simulate and test single cutter assemblies, followed by full-scale mud hammer tools for a variety of loading conditions. TerraTek Corp. in Salt Lake City, Utah, will perform full-scale laboratory testing under simulated downhole conditions at its drilling simulation facility. At least six drilling tests would be completed using two rock types. During each drilling test, parameters such as borehole pressure, rotation, axial load, weight on bit, rotary speed, hammer frequency and amplitude will be measured. During each test, we will measure the rate of penetration for varying rotation, hammer frequency and amplitude.

The fundamental rock mechanics processes associated with percussion drilling have never been fully defined and combined into a comprehensive treatise. Critical processes include dynamic load and energy transfer from the reciprocating and rotating drillbit to the rock, geomechanical processes of dynamic damage and fracture at the bit face, and coupled fluid and cuttings particle flow around and away from the bit. This project will advance the state-of-the-art in each of these areas, providing industry with fundamental algorithms to better characterize the drilling process, a revolutionary new type of simulation technology and new laboratory experimental data. ✧

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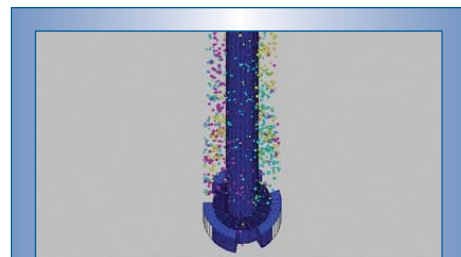
Figure 7. A sample simulation of cuttings transport with high viscosity and high flowrate in a vertical well.
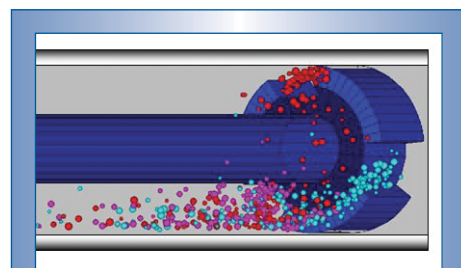
Figure 8. A sample simulation of cuttings transport with low viscosity and low flowrate in a horizontal well.