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Percussion Drilling in Oil Industry: Review and Rock Failure Modelling

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Abstract

There is clear evidence that the percussion drilling can sometimes increase rate of penetration in hard-rock formations[1]. Percussion drilling can also sometimes improve hole geometry, reduces drillstring stresses, generates better and larger cuttings, and lower drilling cost per foot substantially. On the other hand, negative factors such as poor understanding of rock defragmentation, risks in drilling operations, and economical uncertainties have limited the acceptance of percussion drilling technology in the oil and gas industries. Further, 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 simulations tools available to help design and optimize drilling operations. This has led to cost and reliability concerns, limiting the wide-spread application of percussion drilling by industry. Basic science research is required to further advances in this technology, and thereby help industry more economically recover vast untapped gas resources contained in deep, hard-rock environments

A comprehensive research program to significantly advance the fundamental understanding of the physical mechanisms involved in percussion drilling is carried out. Several critical processes are identified for modelling efforts, including drillbit penetration with compression, rotation and percussion, rock response with stress wave propagation, damage accumulation, and failure, and debris transportation inside the annulus after disintegration of the rock. Three failure mechanisms are proposed to account for rock damage and failure during bit-rock interactions, including rock crushing and fracturing by compressive bit load, rock failure due to excessive tensile forces, and rock fatigue by repetive compression-tension type of loading.

Failure models developed for percussion drilling are applied into a numerical simulation code. Initial simulation results reveal relative importance of each failure mechanism to rock breakage, and answer some critical questions such as why, how and when rock fails during percussion drilling. Furthermore a zone of particular interest to modelling efforts is identified under the bit, where rate of penetration (ROP) calculations are made possible.

These achievements advance the fundamental understandings of the physics involved in percussion drilling of hard-rock reservoirs, and lay down a basis for further development of analytical and numerical simulation tools for this very promising technology.

Introduction: History of Percussion Drilling

Percussion drilling is basically the raising and dropping of heavy piercing tools to cut and loosen earth materials. Developed by the Chinese more than 4000 years ago, it was reported to often take two to three generations of workers to complete large wells[2].

In 1859 Colonel F. L. Drake completed the first oil well using a cable tool percussion-type machine. One of the earliest reports of percussion drilling technique occurred in 1949[3]. Since then different terms have been used, such as downhole hammer, percussion hammer, Down-The-Hole hammer, percussive drill, percussive-rotary drill, etc.

Major development and research in percussion drilling have been reported between 1950s and 1960s[4-9]. Significant gains in understanding the percussive mechanism have been also been achieved in the laboratory[5-8]. Some single-well applications have been reported in oilfield for the purpose of demonstrating the effectiveness of percussion drilling[10,11].

Mainly because of frequent mechanical failures, poor understanding and therefore control of drilling operations, and economical uncertainties, wide application of hammer drilling technology to oilfield was not reported until the 1980s. In 1987, Pratt reported that air hammers were tested on 27 wells in Western Canada[12]. Average time to total depth for air/mud drilled wells at one location had been 80 days, compared to the record mud drilled well which took 103 days. Whiteley and England also showed the field applications of air hammer in the Arkoma basin, which has significantly improved air drilling operations through increased ROP, improved hole geometry, reduced drill string stresses, and a substantial reduction in cost per foot[13].

Since the 1990s, oil wells have been drilled to increasing depth, and consequently the encountered rocks have become much harder. Hydraulic hammer or water hammer has been developed to accommodate these new challenges and efficient mechanical designs have been achieved[14,15,16]. These designs, however, are still in pre-field stage.

Throughout its history, theoretical development of percussion drilling technology has lagged behind, compared to the improvement in mechanical designs. This phenomenon is not uncommon in drilling industry as the integrated process of rock drilling involves so many disciplines and complicated physics that rigorous modelling presents significant theoretical challenges.

Pros and Cons

As shown in its history, percussion drilling (even without rotary) can often produce faster penetrating speed than conventional means such as rotary drill or diamond drill, especially in some hard formations such as siliceous granite, sandstone, limestone, dolomite, etc[12,13]. It has been demonstrated that in a medium-hard granite[17], with the same RPM and WOB, the percussive-rotary method is 7.3 times faster than the conventional rotary method, while at the best operational conditions for both methods, percussive-rotary has a 2.3 times advantage in ROP.

In addition to a faster ROP, other advantages of percussion drilling are

- Static and lower WOB. For example, ROP of 3.3m/h was achieved in percussion drilling with a $8^{3/4}$ inch bit and a WOB of 4.5 ton, while in rotary drilling mode WOB needs to be at least 18.5 ton to achieve the same ROP[17];
- Less contact time with rock: only 1 or 2 percent of total operational drilling time[11,17]. This leads to less bit abrasion, hence a longer bit life;
- Less use of other bottomhole assembly;
- Less hole deviation and easier control of deviation problem for straight hole drilling. and,
- Larger cuttings generated, which yields a better representation for geological study.

Some other potential applications of percussion drilling have been proposed recently. For example, the impact of the hammer may serve as a steady seismic signal at the hole bottom, by means of mechanical impact waves transmitted to the rock through the drill bit, and also by means of hydraulic pressure fluctuations in the borehole. Such information may be used to estimate porosity, rock elastic moduli, and synthetic seismograms for comparison with surface seismic data[18]. Bui et al. discussed a possibility to use hammer as a steerable drilling device to provide down-hole rotation[20]. Also impact energy may be exploited for down-hole electricity generation and high-pressure jet intensification, etc.

Because of these attractions, it has been predicted that "…the combination of rotary and percussion-type drilling could make a frontal attack into the drilling technology and open a new era of drilling." [1]

On the other hand, inclusive overall results, risks in operation (such as mechanical failure), and economical uncertainties greatly limit acceptance of percussion drilling technology by operators. There are many unclear but critical issues yet to be solved, such as

- The best ROP with acceptable economics lies more on the basis of field experience rather than a convincing theory. There is no simulation tool that can provide reliable estimation of optimized values for hammer type, number of blows, energy per blow that is directly related to length of the stroke, area of piston, supplied pressure, etc.;
- Hammer bits (cutters) may get balled and lose the ability to drill ahead;
- Excessive hammer energy may cause severe vibration to drill string and rig structure;
- Wellbore may become unstable, such as cavity creation in shale, or even collapse due to reaming or vibration by hammering;
- Performance in shale and other soft rocks is poor; and,
- No evidence of the performance in either directional, horizontal wells, slim hole drilling, or coiled tubing drilling;

Therefore a wide acceptance of percussion drilling may not arrive until these critical issues have been addressed.

A Conceptual Model

A conceptual model of the drilling process is illustrated in Figure 1. There are four fundamental processes that are to be characterized and simulated. These are: 1) drillbit penetration with compression, rotation, and vibration; 2) stress propagation and damage accumulation; 3) rock failure and disaggregation; and 4) cuttings transport away from the bitface 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.

For example, the consequence of drillbit-rock impact leads to rock damage and failure, while rock resistance to the impact slows down and eventually stops the bit penetration. The amount of failed rock influences the volume of the cuttings that must be transported in annulus. If the cuttings are not quickly swept away, the efficiency of percussion drilling is decreased dramatically since next bit-rock impact will be on the failed rock instead of fresh surface.

An integrated simulation tool, which includes a tool model, a rock mechanics model, and a cuttings transport model, is under development[21]. This paper addresses the rock mechanics involved after compressive stress passes from bit to rock, to help answer why, how and when rock fails during percussion drilling.

Physics of Rock Breakage

In rotary drilling bit rotation produces both impact and shearing forces, which may result in two types of rock failures (see Figure 2): crushing because of an axial thrust from the weight on bit (WOB), and fracturing because of shear cutting force. Without bit rotation, rock damages after bit-rock impact in percussive drilling are carried out in several stages[22]: At first the force developed between the bit inserts and the rock builds slowly, and gradually the surface irregularities are crushed and compacted.

Then a rapid increase of the force starts, and subsurface cracks develop in the rock radiating out from the lines of stress concentration at the outer boundaries of the bit inserts. Two main cracks form along a narrow wedge in the rock, which is then crushed and compacted, and the force rises less rapidly. The crushed zone may extend to a depth several times greater than the actual depth of bit penetration[5].

Finally, large fragments are suddenly fractured out along a curved trajectory up to the surface adjacent to the crushed zone (i.e. in the form of flat conchoidal flakes). As the side walls for the crushed wedge are removed, the force drops. A new rock surface is now available, and the process is repeated if failed rock is cleared efficiently from the impact surface.

Simulation of Rock Mechanics in Percussion Drilling

Geomechanical modeling efforts are carried out to simulate stress wave propagation, rock damage and failure during bit-rock impact, and to eventually predict ROP. Numerical simulations are carried out with aid of a finite-difference based numerical code[23].

A One Column Model for Rock Failure

To develop and test the rock failure algorithm, a one column rock model of 16 elements is developed with stress wave input, failure models, and dynamic features. Rock is modeled as a Mohr-Coulomb type of elastoplastic material with strain hardening and softening characteristics. Rock properties, such as moduli and strengths, are listed in Table 1. The rock total strain increment is a sum of an elastic strain increment $\Delta\varepsilon^{e}$, a shear plastic strain increment $\Delta\varepsilon^{ps}$, and a tensile plastic strain increment $\Delta\varepsilon^{pt}$:

$$\Delta\varepsilon = \Delta\varepsilon^{e} + \Delta\varepsilon^{ps} + \Delta\varepsilon^{pt} \qquad (1)$$

The yield surface (*f*) where rock starts to behave plastically is defined by dynamic stresses (σ_{ij}), plastic strain ($\varepsilon^{P} = \Delta\varepsilon^{ps} + \Delta\varepsilon^{pt}$), and a hardening parameter (κ) that describes rock strength behavior with plastic deformation:

$$\vec{f} = f(\sigma_{ij}, \varepsilon_{ij}{}^{p}, \kappa) \qquad (2)$$

Three failure mechanisms are proposed to account for rock damage and failure during its post-yield state, including rock crushing and fracturing by compressive bit load, rock failure due to excessive tensile forces, and rock fatigue by repetive compression-tension type of loading. Corresponding to each mechanism, three rock failure criteria have been developed to determine where and how the rock fails during percussive drilling:

- Critical compressive strain criteria (ε^{p}). It states when rock fails due to excessive compressional strain in loading direction;
- Critical shear plastic strain criteria (ε^{ps}). It states whether rock experiences shear failure; and,
- Tensile failure. This type of failure most likely occurs during bit retreat from the impact, when rock has experienced maximum compression and starts to partially retrieve its deformation. The rock will fail if minimum principal stress (σ_3) is beyond tensile strength (σ_T):

$$\sigma_3 > \sigma_T \qquad (3)$$

Rock fatigue due to cyclic loading is partially simulated through the application of plastic post-peak softening. Another approach is to implement some empirical correlation of rock strength with number of loading cycles based on lab results (e.g. the curve shown in Fig. 3)[24].

A stress wave with multiple impulses, which varies with time during hammer impact and decays monotonically during hammer retreat, is applied as a loading condition. Rayleigh damping is selected to partially account for energy loss in the rock because of internal rock friction or interface slippage.

A 3D Stress Model for Initial Evaluation

A 3D numerical model is constructed for initial stress analysis. A mesh block with 20,000 elements is generated to simulate the rock formation that is drilled vertically by a percussive drillbit. The model size is 75m x36m x72m in X, Y, and Z directions, respectively (see Fig. 6). A vertical stress of 15MPa from overburden rocks is loaded evenly on the top elements, while horizontal stresses in far-field are 10MPa. The bottom elements are fixed in Z direction. Meshes near the wellbore and below the drill bit are further refined so that profiles of stress and strain can be more detailed. Rock is modeled as a type of elastoplastic material with bulk and shear moduli of 7.2 GPa and 12 GPa, respectively.

At a peak vertical loading stress of 50MPa, the vertical displacement is shown in Fig. 7. High stress and displacement concentrate in the rock below the bit and extend vertically to about 3 to 4 times the bit diameter. The deformation zone, as indicated in the figure, is of particular interest for the drilling simulation because its size determines how fast drilling progresses.

Simulation Results and Discussions

Parameters used are listed in Table 1. A stress wave of 5 impulses per second is loaded on the top of a column of rock elements with 1.5MPa of confining stress.

The initial impact velocity is 6m/s and each impact lasts 0.3 milliseconds before the bit retreats. Effect of mud pressure of about 1MPa is also considered.

Impact Stress with and without Mud Pressure

For an individual impact, stress and velocity at the top of rock surface where the impact occurs are plotted in Fig. 7. Mud pressure of 1MPa is assumed to be constant on the loading surface as fluctuations of fluid pressure inside wellbore due to bit movement are too sophisticated to consider simultaneously.

Applied impact velocity is a pulse with the maximum of 6m/s. After the impact, the bit is lifted away from the rock and the applied velocity becomes zero. Correspondingly, stress at the top of the rock reaches as high as 23MPa during the impact, and then reduces to a low magnitude close to the mud pressure but with fluctuations.

Even though it can oscillate and decrease to as low as about zero (at 0.001 second), the rock stress at the impact is still positive, which means the rock is in compression throughout the impact. However, when mud pressure is relieved, as shown in Fig. 8, the rock stress can become negative. This indicates the rock is in tension for a short period right after the bit retreats. Since rock tensile strength is much lower than its compressive strength (usually on the order of one eight to one tenth), rock may experience tensile failure at this point. This is consistent with the observation that ROP decreases with increase of BHP in percussion drilling[8].

As a conclusion, one reason for less efficiency of hammer drilling technology in higher mud pressure environment may due to more restrain in rock tensile state after the bit retreats, and therefore less likely occurrence of tensile failure.

Cyclic Impacts and Bit Advancement

Fig. 9 describes rock stress-strain curves when multiple impacts are applied. Rock failure models are disabled in this simulation so that stress-strain curve can be plotted on the same rock element. Clearly rock peak strength has been weakened after each cycle, mainly because of rock plastic deformation and damage accumulation.

With the failure models activated, rock failure state will be determined with various failure criteria, based on stress and strain magnitude at a certain amount of timesteps. If any criterion has been met, failed rock will be deleted from the rock model, rock geometry and properties will be updated, and the loading stress pulse will move on to the next element and continue to compress the rock, in addition to its previous deformation. Otherwise, only rock properties will be recalculated based on the fatigue model. Fig. 10 describes how the hammer bit advances with simulation time. Each sudden jump represents one element failure and removal.

Rock Failure Patterns

Besides generating the plot of bit advancement vs. time, a history file of rock failure is also created. It documents not only how many elements have failed so far, but also how does each element fail during each impact. For example, Element 16 (at the top) has failed at the first impact because of high compressive loading, while Element 15 (second to the top) has failed due to rock tensile failure during bit retreat, since the impact between the bit and the rock lasts only 0.3 milliseconds and Element 15 fails at 0.39 milliseconds.

As for the case tested, about 75% of elements have failed due to excessive tension stress and only 25% of the rock elements have failed because of high compressive loading. It should be noted that these numbers may vary quite differently from case to case, depending not only on stress state and rock properties (such as modulus, strengths, friction angle, etc.), but also on wave properties (such as frequency, contact time, magnitude, etc.).

Next Step

The material models and algorithms developed in the one-column simulation are to be implemented into a 3D wellbore case. Coupling with a hammer model for drillbit and a particle model for cuttings transport in annulus, an integrated simulation tool is under development. After this tool is developed, a set of full-scale laboratory tests will be carried out. The purpose of the tests is to verify the physics and mechanisms described in the theoretical models, and also to validate the simulation tool.

Conclusions

Based on published experiment and field documentations, processes and physics of percussion drilling (with or without rotary) have been described. Three main processes are identified for modelling efforts, drillbit penetration with compression, rotation and percussion, rock response with stress wave propagation, damage accumulation, and failure, and debris transportation inside the annulus after disintegrated from rock. Three failure mechanisms are proposed to account for rock damage and failure during bit-rock interactions, including rock crushing and fracturing by compressive bit load, rock failure due to excessive tensile forces, and rock fatigue by repetive compression-tension type of loading. Each is modeled in a numerical simulation code. The effect of mud pressure is also considered and discussed.

Initial simulations indicate rock may fail due to either high compressive loading from bit-rock impact or excessive tension during bit retreat from the impact. The results reveal relative importance of each failure mechanism to rock breakage. Even though it varies significantly from case to case, rock may more likely experience tensile failure than compressive failure during percussion drilling, due to its low magnitude of tensile strength. With consideration of mud pressure, it is found rock may rarely become tensional if the pressure is high enough during bit retreat. This is consistent with the findings that the efficiency of percussion drilling decreases with high mud pressure or deep borehole.

The model developed above can describe when, where, and how rock fails and produce a penetration result and history with dynamic time simulated. These achievements advance the fundamental understandings of the physical mechanisms involved in percussion drilling, and will be a part of further development of a coupled simulation tool.

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Nomenclature

f = *Rock failure surface*
σ = *Rock stress, Pa*
σ_T = *Rock tensile strength, MPa*
$\varepsilon^e, \varepsilon^p$ = *Rock elastic and plastic strains, respectively*
$\varepsilon^{ps}, \varepsilon^{pt}$ = *Shear and tensile plastic strains, respectively*
κ = *Hardening parameter in plasticity theory*
BHP = *Bottom Hole Pressure*
ROP = *Rate of Penetration*
RPM = *Rotation per Minute*
UCS = *Uniaxial Compressive Strength*
WOB = *Weight on Bit*

References

1. Samuel, G.R.: “Percussion Drilling…Is It a Lost Technique? A Review., SPE 35240, the Permian Basin Oil & Gas Recovery Conference, Mildland, TX, USA, Mar 27-29, 1996.
2. Treadway, C.: “Percussion and Down-The-Hole Hammer Drilling: Yesterday and Today”, *Water Well Journal*, v. 51, No.7, (1997) 55-59.
3. Harpst, W.E., and Davis, E.E.: “Rotary Percussion Drilling”, *Oil and Gas Journal*, (Mar, 1949) 182-187.
4. Wanamaker, J.A.: “Rotary Percussion Drilling in West Texas”, *World Oil*, (Sept 1951) 182-187.
5. Faihust, C., and Lacabanne, W.D.: “Some Principles and Developments in Hard Rock Drilling Techniques”, Proc. 6th Ann. Drilling and Blasting Symposium, Minnesota Uni., 15-25. 1956.
6. Topanelian Jr.: “Effect of Low Frequency Percussion in Drilling Hard Rock”, *AIME – Petroleum Transaction*, (1958) v.213.
7. Simon, R.: “Transfer of Stress Wave Energy in the Drill Steel of a Percussive Drill to the Rock”, *Journal of Rock Mechanics and Mining Science*, (1964).
8. Fish, B.G.: “Research in Rock Drilling and Tunneling”, *Min. Elect. Mech. Engr*, (Feb 1961) 1-13.
9. McGregor, K.: The Drilling of Rock, CR Books Ltd., London, 1967.
10. Smith, F.W., and Kopczynksi, W.: “Oilfield Percussion Drilling”, SPE 222, the 32nd Annual California Regional Meeting of SPE, Bakerfield, CA, USA, Nov. 2-3, 1961.
11. Bates, R.E.: “Field Results of Percussion Air Drilling”, SPE 886, the 39th SPE Annual Fall Meeting, Houston, TX, USA, Oct. 11-14, 1964.
12. Pratt, C.A.: “Modifications to and Experience with Percussion Air Drilling”, SPE/IADC 16166, the 1987 SPE/ IADC Drilling Conference, New Orleans, LA, USA, Mar. 15-18.
13. Whiteley, M.C., and England, W.P.: “Air Drilling Operations Improved by Percussion-Bit/Hammer-Tool Tandem”, SPE 13429, *SPE Drilling Engineering*, (Oct 1986) 377-382.
14. Kong, J., Marx, C., and Palten, P.J.: “Mathematical Simulation of A Spring-Free Hydraulic Drilling Hammer and Verification of the Results by Experiment”, *Erdol Erdgas Kohle*, v. 112, No.1, (1996) 19-25.
15. Giles, C.A., Seesahai, T., Brooks, J.W., and Johnatty, W.: “Drilling Efficiencies Provided by Hydraulic Thrusting Devices”, the AADE 2001 National Drilling Conference, Houston, Texas, USA, Mar 2001.
16. Tibbitts, G.A., Long, R.C., Miller, B.E., Judzis A., and Black, A.D.: “ World's First Benchmarking of Drilling Mud Hammer Performance at Depth Conditions”, IADC/SPE 74540, the IADC/SPE Drilling Conference, Dallas, TX, USA, Feb 26-28, 2002.
17. Melamed, Y., Kiselev, A., Gelfgat, M., Dreesen, D., and Blacic, J.: “Hydraulic Hammer Drilling Technology: Developments and Capabilities”, *Journal of Energy Resources Technology*, v.122, No.1, (2000)1-8.
18. Minear, J.W., Heysse, D.R., and Boonen, P.M.: “Initial Results from An Acoustic Logging-While-Drilling Tool”, SPE 36543, 1996.
19. Pixton, D., and Hall, D.: “Advanced Mud Hammer Systems”, DOE project #DE-FC26-97FT34365, Novateck Inc., Provo, UT, USA, 2002.
20. Bui, H., Meyers, J., and Swadi, S.: “Steerable Percussion Air Drilling System”, DOE contractor review meeting, Baton Rouge, USA, Apr 1995.
21. Han, G., and Bruno, M.: “Fundamental Research on Percussion Drilling: Improved rock mechanics analysis, advanced simulation technology, and full-scale laboratory investigations”, DOE project #DE-FC26-03NT41999, Terralog Technologies USA, Inc., Arcadia, CA, Apr 2004.
22. White, C.G.: “A Rock Drillability Index”, Quarterly of the Colorado School of Mines, v.61, No.2, April 1969.
23. Itasca Consulting Group, Inc.: “FLAC3D: Theory and Background”, Minneapolis, Minnesota, USA, 2002.
24. Ewy, R.T., Bovberg, C.A., Chen, G., Jansson, R., and Pepin, G.: “Fatigue Testing of Hollow Cylinders and Application to Injection Well Cycling”, ARMA/NARMS 04-464, Gulf Rocks 2004, the 6th North America Rock Mechanics Symposium, Jun. 5-9, 2004.

Table 1. Input parameters for 1-column rock mechanics model in percussion simulation

Model Size			Moduli		Rock Density (kg/m^3)	Cohesive Strength (MPa)	Friction Angle	Tensile Strength (MPa)	Confining stress (MPa)	Dynamic time to solve (sec)	Frequency of impact (1/sec)	Maximum impact velocity (m/s)
x	y	z	Shear (GPa)	Bulk (GPa)								
1	1	16	12	7.2	2.65×10^3	5.12	30	1.2	1.5	1	5	6

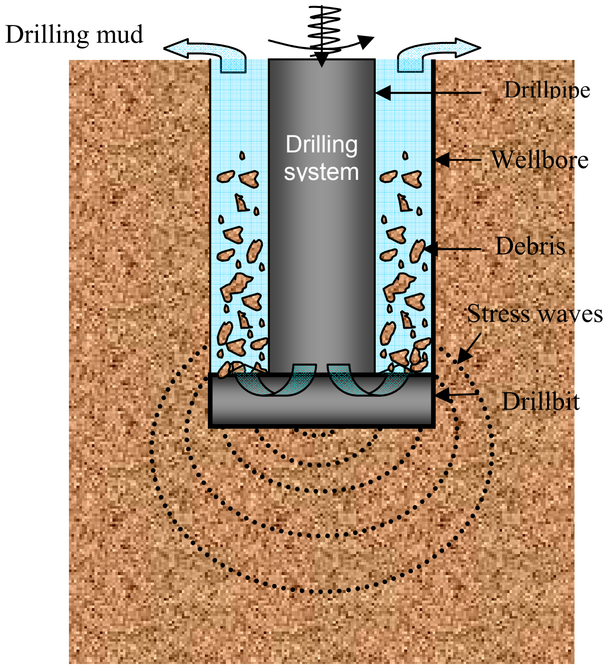


Fig. 1. Conceptual model for percussion drilling simulation

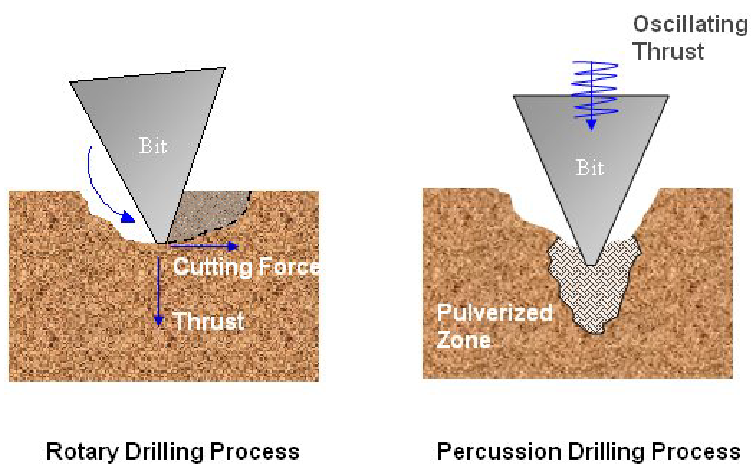


Fig. 2. Rock defragmentation in both rotary drilling and percussion drilling

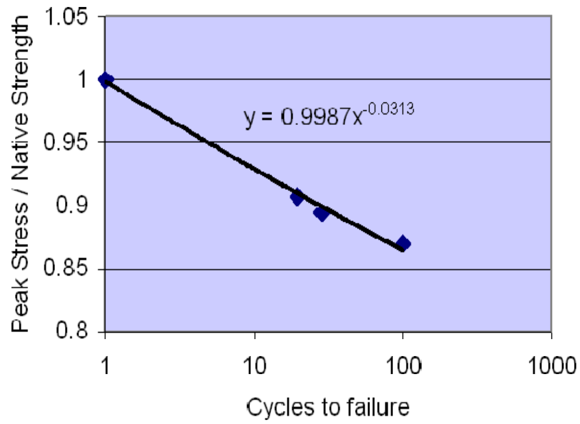


Fig. 3. Rock fatigue due to cyclic loading[24]

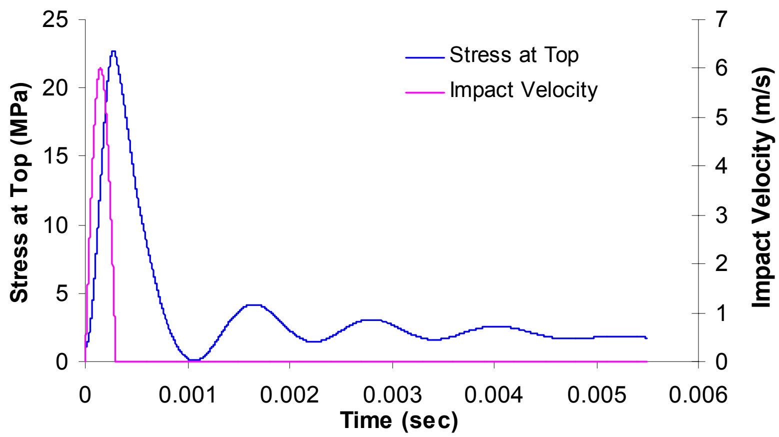


Fig. 4. Impact stress at the rock surface after one percussion with mud pressure

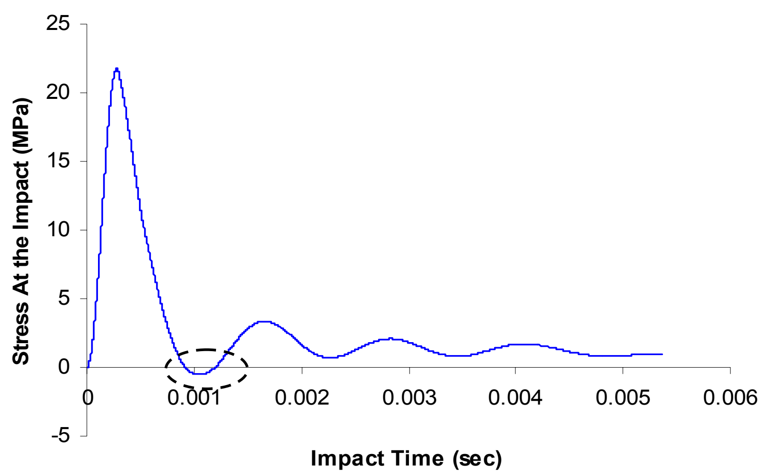


Fig. 5. Impact stress at the rock surface after one percussion without mud pressure

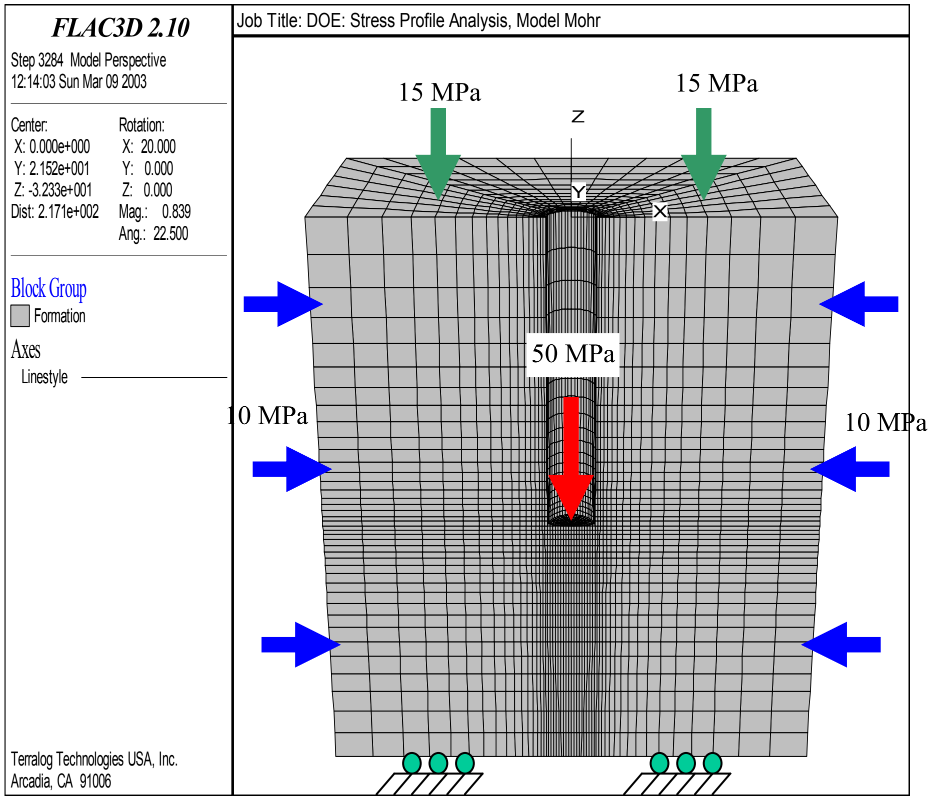


Fig. 6. Meshes generated for 3D stress study in percussion drilling

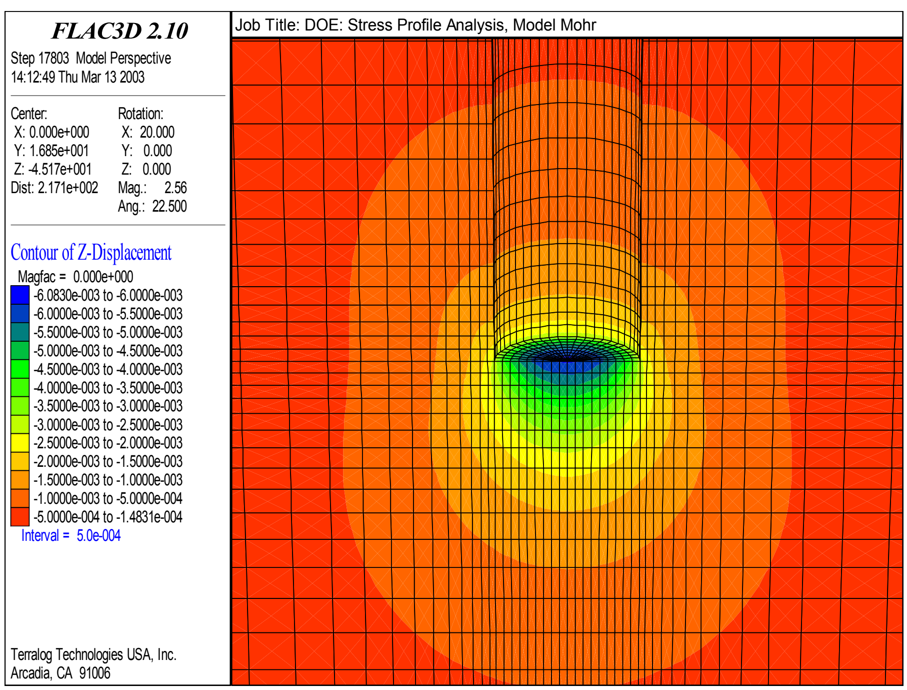


Fig. 7. Rock vertical displacement at the peak impact stress

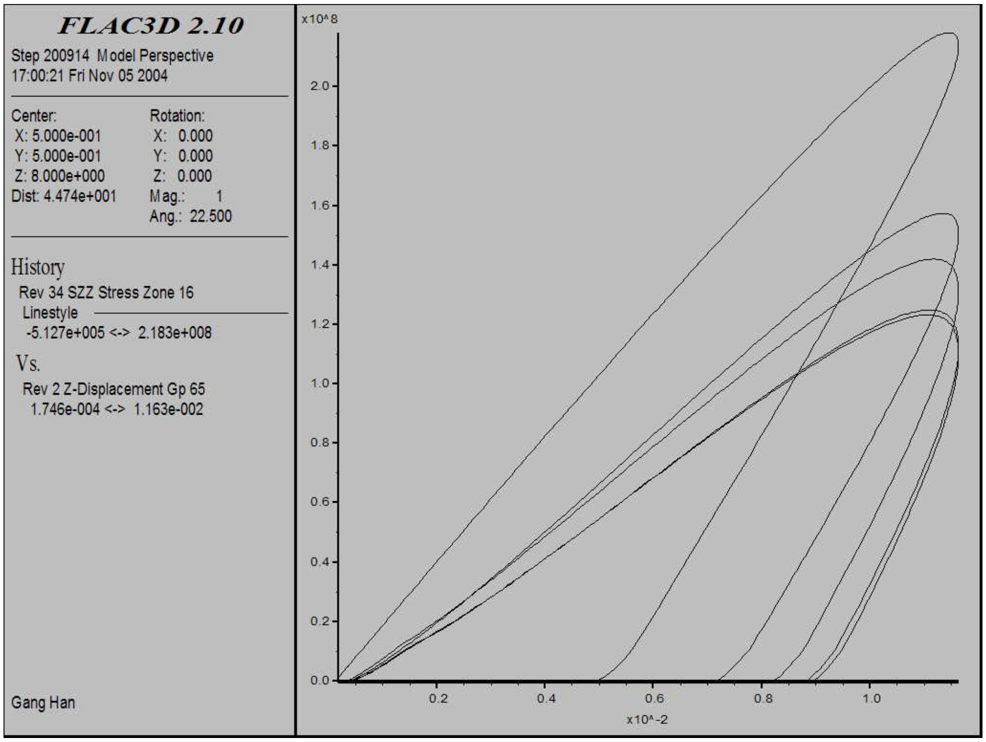


Fig. 8. Simulation of rock stress-strain curve during multiple impacts

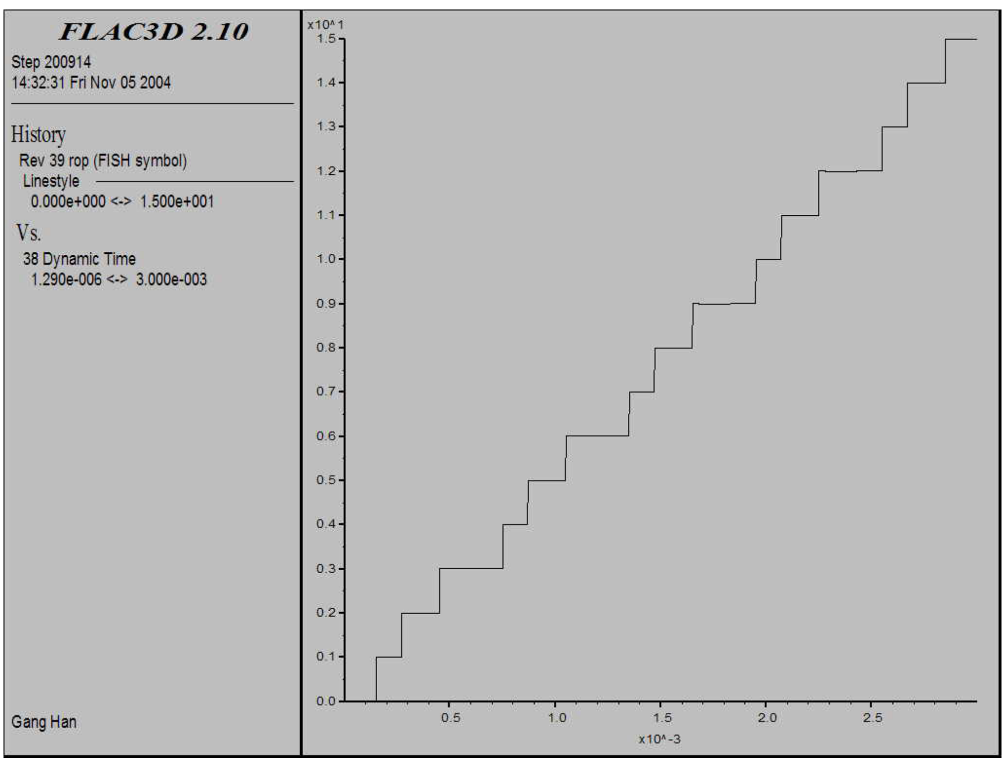
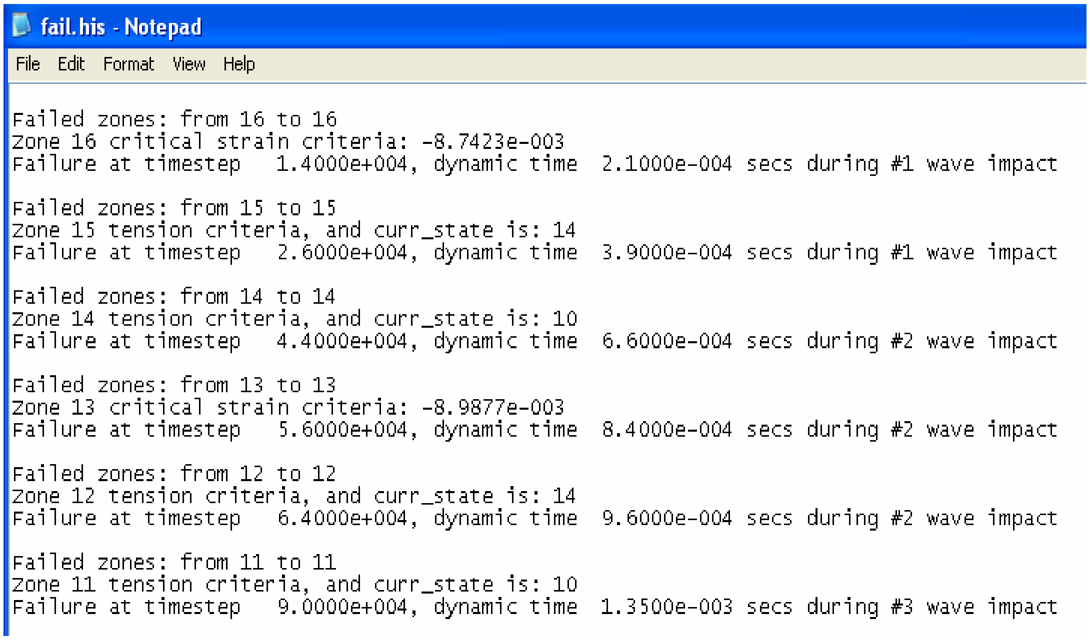


Fig. 9. Simulated ROP during percussion drilling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Failed zones: from 16 to 16
Zone 16 critical strain criteria: -8.7423e-003
Failure at timestep   1.4000e+004, dynamic time  2.1000e-004 secs during #1 wave impact

Failed zones: from 15 to 15
Zone 15 tension criteria, and curr_state is: 14
Failure at timestep   2.6000e+004, dynamic time  3.9000e-004 secs during #1 wave impact

Failed zones: from 14 to 14
Zone 14 tension criteria, and curr_state is: 10
Failure at timestep   4.4000e+004, dynamic time  6.6000e-004 secs during #2 wave impact

Failed zones: from 13 to 13
Zone 13 critical strain criteria: -8.9877e-003
Failure at timestep   5.6000e+004, dynamic time  8.4000e-004 secs during #2 wave impact

Failed zones: from 12 to 12
Zone 12 tension criteria, and curr_state is: 14
Failure at timestep   6.4000e+004, dynamic time  9.6000e-004 secs during #2 wave impact

Failed zones: from 11 to 11
Zone 11 tension criteria, and curr_state is: 10
Failure at timestep   9.0000e+004, dynamic time  1.3500e-003 secs during #3 wave impact
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Fig. 10. Failure history of each rock element