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Effect of Pore Pressure on Single Cutter Forces (Proposal)

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This report is prepared for TUDRP Advisory Board Meeting November 13-14, 2006, Tulsa-Oklahoma.

Introduction

The drilling industry through the years has evolved in such a manner to provide efficient means for reaching target oilfields below the surface of the earth. Problems have been encountered and solutions have been sought after. Problems such as premature bit failure, drillstring vibrations, thermal durability, bit wear, bearing failure and many others have been and still are the focus of much research. The final objective of all the research is to reach the target below the surface with minimum cost.

In spite of advancements, the drilling industry still suffers from low rates of penetration and there is a need to fully understand the mechanisms involved in drilling formations at depth. Among all parameters investigated in this matter, pore pressure is one with much importance and research in this area has been limited.

Besides blowouts and lost circulation, which impose huge monetary losses, pore pressure affects the drilling industry in other not so obvious manners. By influencing the mode of rock failure and the efficiency of chip removal, formation pore pressure is a major factor that contributes to the rate of penetration of the drill bit, and thus drilling efficiency and the drilling economy.

Mechanical specific energy is a concept introduced to the drilling industry by Teale[1] to provide an applicable method to measure drilling efficiency in different environments. Mechanical specific energy is the energy required to remove a unit volume of rock and has the units N/m2 (psi). While drilling rock at atmospheric pressures in laboratory experiments, specific energy is close to the UCS of the rock. Thus drilling efficiency is measured on the rig by comparing the energy spent on drilling and the rock strength. While it has gained overwhelming acceptance from the industry, the available models do not fully account for the effect of formation pore pressure on rock strength and the rate of penetration.

While general studies on the effect of pore pressure on the rate of penetration have been made, a fundamental study of the effect of pore pressure and its changing behavior during rock cutting by a single cutter should be performed. Such a study provides the industry with the means to gain better understanding of the mechanisms involved in rock cutting and helps with designing methods for higher drilling efficiency.

Statement of Problem

Failure of a rock is due to the stresses imposed on it. The stresses imposed on the rock by the bit and the confining stresses imposed by the surrounding rock or the drilling fluid are not the only stresses governing rock failure. The fluid in the rock pore space is pressurized and carries a portion of the normal load across the failure surface. This causes reduction in the overall rock strength by reducing the frictional forces acting on the failure plane. It is the effective stress, the difference between externally applied pressures and pore pressure, which governs the rock failure mechanism[2].

When rock chips are produced from the indentation of the drill bit tooth into the formation, they have to be removed in order for the next tooth to advance into the formation. There are forces aiding the removal process, such as the elastic rebound in the chip, the mechanical actions of the bit tooth and the hydraulic forces from the drilling fluid jet. Opposing the forces above are forces known as chip hold down forces, which act on the newly formed chip and tend to hold it in place. These forces are produced due to the pressure differential over the chip and are proportional to the area of the chip. The

pressure differential over the chip is related to the pore pressure, its reduction due to the formation of the crack and fluid invasion into the space induced by the crack[3].

While the concept of mechanical specific energy is being widely used today, none of the existing models fully take into account the effect of pore pressure on the mechanical specific energy. These models implement the mechanical specific energy of rock by data from the uniaxial or triaxial strength tests with some minor modifications and do not implement the effect of pore pressure along with other parameters on the rock failure mechanism and the chip removal mechanics.

Objectives

(1) To study the effect of pore fluid pressure and aspects related to it on the mechanisms of rock failure and chip removal.

(2) To provide a mathematical model which takes into account the effect of pore pressure and other parameters on the forces exerted on the cutters and the mechanical specific energy required for drilling a formation.

(3) To perform experimental studies on the effect of pore fluid pressure on rock failure and chip removal, pending available time and funds.

Preliminary Literature Review

The first few days of drilling are spent drilling a major part of the formation with high rates of penetration. The rest is spent drilling the minor deep formations with really low rates. Many have investigated this reduction of rate of penetration with depth and have attributed it to increasing differential pressure, increasing hydrostatic head, increasing in-situ stresses, decreasing porosity with depth, and chip hold down[4].

Chip hold down effect

Garnier and Van Lingen[5] studied the effect of pore pressure on the rate of penetration into different rocks under confining, overburden and pore pressures. They

used water and mud in their experiments. They observed that with equal borehole, pore and confining pressures, the rate of penetration in permeable formations drilled with water does not change with increasing the pressures, while for slightly permeable Belgian limestone, the rate of penetration decreases continuously. With mud, however, the rate of penetration decreases up to a certain pressure and from then on no further reduction is observed. In Belgian limestone the continuously dropping curve of mud matches exactly with that of water. Since pore and confining pressures are equal, rock strengthening is not the explanation for these observations.

Garnier and Van Lingen[5] proposed that since pore pressure and mud pressure are equal, a downward force of static origin is not present, but instead a downward force of dynamic origin is produced when a chip is made and is being lifted. This lift causes vacuum under the chip with only three ways to fill it in: (1) drilling fluid flowing into the crack, (2) filtrate flowing through the pores of the chip and (3) formation fluid flowing through the pores of the rock. They assumed the initial width of the crack to be small enough to resist the first fluid flow and the plastering of mud sufficient so that the second source of fluid flow would also be ineffective. The third source depends on the permeability of the rock, the rate of chip removal and the amount of differential pressure between the vacuum created under the chip and the formation pore pressure. Further experiments with mud pressures higher than the pore pressure proved that the hold down force is proportional to the difference between the mud column pressure and the vacuum pressure created under the chip.

Through further experiments Van Lingen[6] observed that the reduction factor accounting for the effect of chip hold down is different for different bits. This difference has to do with the effect of pore pressure on the work of each single cutter. The studies were performed on a macroscopic basis and sought the effect of pore pressure on the overall drilling action of the whole bit. Van Lingen suggested that cutting angle and bluntness of the cutting elements affect the reduction factor, but he did not analyze their effects thoroughly. With further experiments he observed that both the plastering properties and the circulation rate of the mud affect the dynamic hold down. Feenstra and Van Leeuwen[7] observed through experiments that jet velocity affects dynamic hold down

and can be used to improve chip removal and increase rate of penetration. A mathematical model however was not presented.

Differential pressure and the effective stress

Change of rate of penetration has been observed in formations where abnormal pore pressures are encountered[8]. Warren[4] calculated the bottomhole stresses by including the effect of pore pressure in the stresses on the bottomhole rock. He argued that during drilling, the overburden pressure of the drilled rock is replaced with the mud column pressure. Since the mud column needs only to overcome the pore pressure, its pressure gradient is much lower than the average overburden pressure gradient. The average overburden pressure gradient is 1 psi/ft while the average pore pressure gradient is 0.465 psi/ft. As a result the bottomhole rock will encounter a decrease in overburden pressure and will expand causing the pore pressure to decrease in impermeable formations which cannot compensate (in time) the fluid to fill in the increased volume. In this way he calculated through finite element methods the actual differential pressure occurring in impermeable formations and justified the decrease in rate of penetration in part to rock strengthening due to the induced differential pressure. For permeable formations such as sandstones pore pressure will equalize to the mud column pressure in the immediate vicinity of the bottomhole and will gradually change in the far field. He then interpreted the strengthening of permeable rocks in deep wells as being due to a short pressure gradient over the mud filter cake. In this study, only the changes in the bottomhole stresses were calculated and it was assumed that the rock is impermeable. The effect of stress changes during the cutting action of the bit cutters was not considered.

Kolle[9] argued that poroelastic relaxation is unlikely to influence drag bit cutting at typical cutting depths. He suggested that pore volume dilatancy in impermeable rocks at high strain rates causes pore fluid cavitation resulting in a differential stress equal to the applied hydrostatic pressure. He generated a one dimensional model of dilatancy hardening ahead of a drag bit cutter which explicitly accounts for rock poroelasticity, strength and diffusion effects to predict the magnitude of confining pressure in rocks. He performed experimental tests with fresh water at elevated pressures, and showed that strain rate has effect on rock strength for impermeable rocks. Only the general trend of

the experimental data could be explained with the dilatancy hardening model he proposed.

Mechanical specific energy

The concept of mechanical specific energy was introduced in drilling by Teale[1] as the mechanical energy required for removing a unit volume of rock. It is related to torque, rotary speed, weight on bit and the rate of penetration, all of which are the main parameters recorded during drilling operations. As a result, the concept has provided a way to measure the drilling efficiency by monitoring the amount of mechanical specific energy being put to the system and the minimum required specific energy to drill the rock[10].

Caicedo[11], inspired by the work of Warren in calculating the induced differential pressure and its effect on strengthening of impermeable rocks, proposed a linear model to account for the strengthening of rocks due to differential pressure in a range of high permeability to essential impermeability. He then incorporated his model in the calculation of specific mechanical energy to predict the rate of penetration. He estimated the permeability of the formation from its porosity, and used so many correction factors to account for the effect of different parameters that the practicality of his model is brought into question.

Detournay and Tan[12] investigated the effect of different pressures on the mechanical specific energy for drilling shales. Through experimentation, they confirmed the independence of mechanical specific energy from pore pressure in shales. They attributed this effect to the cavitation of pore fluid due to dilatancy. They also observed that in some cases, the mechanical specific energy reduced with increasing confining pressures. They proposed that high cutter rake angles impose additional pressures on rock which limits dilatancy and pore pressure drop. They did not model these effects mathematically.

Rock failure mechanisms

The mechanism of rock failure is of much importance in modeling failure and production of rock chips. Rocks show different behavior under different confining

pressures, moving from a brittle failure behavior in low confining pressures to a ductile failure behavior in higher confining or differential pressures[13]. Maurer in his experiments on shear failure tests showed that ductile failure behavior occurs when the rock to rock friction along fractures exceeds the shear strength of rock[14]. Thus, disregarding a few plastic behaving shales, ductile failure is a result of the production of a fracture along with high rock-to-rock friction. This friction is highly dependent on the effective normal force acting on the failure surface, and thus is strongly related to the pore pressure existing at the failure surface and its change with the movement of different fluids into it.

Garcia modeled the stresses involved in the production of rock chips by assuming a quasi-static rock-cutter interaction that accounts for friction due to the sliding of rock chips on the face of the cutter and friction between worn flat areas of the cutter and unbroken rock beneath the cutter[15]. He also included in his model the sliding friction of the rock chip on the unbroken rock when confining pressures are high enough to hold down the chip quite firmly. He showed in his computations that during the production of a rock chip both types of failure (brittle and ductile) can be present due to high frictional stresses induced by high back rake angles. He then mentioned the dominating effect of frictional stresses acting on the worn cutters in the cutting process. While thoroughly studying the mechanisms of rock failure during the cutting action of a single cutter, Garcia did not take into account the effect of pore pressure on the induced stresses. While he attributed much of the stresses acting on the rock and the cutter due to the frictional forces, he bypassed the dominating effect of pore pressure on the normal forces providing the friction by performing his calculations with the effective stress and assuming a zero pore pressure.

It is evident from the literature that so far the study of pore pressure and its effects on drilling have been from a general viewpoint on the rate of penetration and have been mainly performed for extreme cases of impermeable or highly permeable rocks. While there have been fundamental studies on the forces acting on a single cutter during drilling, none of these studies have fully incorporated the effect of pore pressure and its changing behavior during the cutting action of a single cutter. Although for simplifying purposes single cutter studies have accounted for pore pressure by performing the calculations based on the effective stress, a through study is proposed to consider the

effect of changing pore pressure during the cutting action of a single cutter. Such a study would provide the industry with means to design approaches for higher efficiency drilling.

Approach

Theoretical

Through detailed studies, a finite element model for prediction of cutting forces during the rock-bit interaction that accounts for the effect of changing pore pressure will be prepared. The model will be implemented through computer codes and the results will be analyzed. Results from the computer implementation will be compared with that of available commercial FEA programs.

Experimental

The proposed project comprises both theoretical studies and experimental investigations. The high pressure dynamic triaxial cell located at the University of Tulsa North Campus, through some reparations, would be able to assist the experimental work for this research. The test facility has the following capabilities: (refer to the appendix for schematic and pictures)

- Three independent pressures (pore, overburden, and confining pressure) can be supported up to 15,000 psi.
- With the 10 horsepower dc motor, rock sample rotation is provided with up to 350 fpm of linear cutting speed and a maximum of 1000 pounds drag force.
- The assembly provides the means for adjusting depth of cut and side rake angle.
- Triaxial orthogonal forces and depth of cut can be measured during rock cutting.
- Depth of cut of up to 0.3 in. with a resolution of 0.001 in. is provided.
- Maximum vertical load of 2000 pounds can be applied to the cutter.

Through experimental studies, single cutter forces will be measured during the cutting action under different pressures and the results will be compared with the theoretical studies.

Scope of Work

Theoretical

The mechanism of rock chip production at downhole conditions will be modeled. The effect of the pore pressure and its changing behavior in this mechanism will also be modeled. Computer codes will be written to implement the mathematical model and calculate stresses and forces on the cutter during the cutter-rock interaction. Results from the mathematical model will be compared and interpreted with experimental data, if available. As mentioned, experimental work using the single bit cutter depends on available time and funds. Necessary modifications to the model will be applied. At the end the effect of pore pressure on the mechanical specific energy will be presented and analyzed.

Experimental

Once the test facility is operational, pending available time, experimental tests will be conducted to verify the model provided. In the first series of tests, single cutter forces will be measured while cutting Carthage limestone under the same borehole and pore pressures. In the second series of tests, an overbalance between the overburden and pore pressure will be maintained and single cutter forces will be measured.

The cutters will have the same properties. Pending available time, there is possible consideration of different cutters in the experimental tests. Also other rock types might be considered if available.

Preliminary Test Matrix*

Confining Pressure Range psi (MPa)	Overburden Pressure Range psi (MPa)	Pore Pressure Range psi (MPa)	Rock Types
3000 - 10000 (20 – 70)	**3000 – 10000 (20 – 70)**	**3000 - 5000 (20 – 35)**	**Limestone** **(if available, other rocks are also considered)**

Preliminary Timetable

Tasks \ Time	2006		2007				2008	
	8-9	10-12	1-3	4-6	7-9	10-12	1-3	4-6
Literature review								
Model development								
Test facility preparation*								
Single cutter tests*								
Test data analysis*								
Final report								

* subject to available time and funds

Deliverables

1- Mathematical models to predict the effect of pore pressure on cutter forces and the mechanical specific energy required for drilling.

2- Computer codes that implement the mathematical model for computational purposes.

3- An experimental data base on the effect of pore pressure on cutting forces (tentative).

4- Semi-annual Advisory Board Meeting (ABM) progress reports and a Final Report.

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Appendix

Pictures and schematic of the test facility

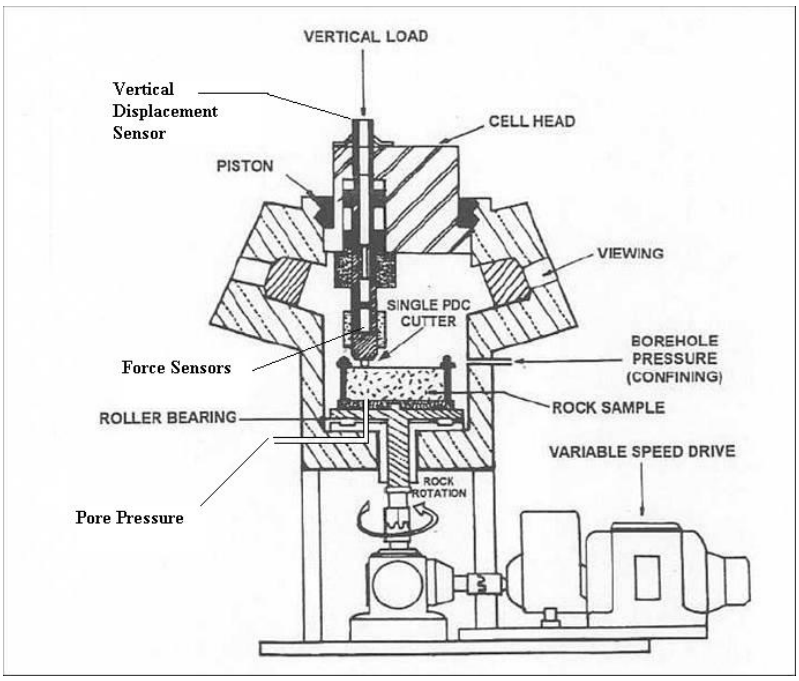

Fig. 1: Schematic diagram of the high pressure cell

Fig. 2: Pressure cell head assembly

Fig. 3: Pressure cell and dc motor

Fig. 4: The pressure system