



New Confined Compressive Strength Calculation Improves Bit Selection and Bit Performance

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Abstract

It has become standard practice to use log-based rock strength analysis to plan wells and analyze bit performance. Several methodologies in use characterize rock strength in terms of confined compressive strength (CCS), but the standard most widely used by drill bit specialists is unconfined compressive strength (UCS). The use of UCS is somewhat problematic in that the apparent strength of the rock to the bit is typically something different than UCS. Those who understand bit performance are aware of this problem. It is widely accepted and documented that bit performance is greatly influenced by mud pressure and the difference between mud pressure and pore pressure. However, there is not an industry standard or widely used methodology to account for these effects.

A globally applicable solution and methodology has been developed and is in use by ChevronTexaco. The method involves log-based workflows and a combination of conventional and somewhat innovative rock mechanics principles. The method is robust, based on fundamental and/or first principles, and requires little or no calibration. Any required calibration is simple and intuitive, and lessons learned in one location can be applied anywhere else. This paper presents the new methodology, field and lab data that validate or quantify the degree of improvement obtained by using the new method, and a case history that illustrates the problem of using UCS and the benefit of the new method. The paper also encourages adoption of this method or another equally practical and robust CCS calculation as the new standard for bit/BHA selection, performance modeling, and analysis.

Introduction

During the late 1990's, Chevron Exploration and Production Technology Company (EPTC) initiated work on a project to improve drilling performance and pre-drill drilling performance prediction based on a mechanical earth model (MEM). Several of the desired and required components of this project were pre-drill bit selection, rate of penetration (ROP) prediction, and bit life prediction. Another objective of the project was the integration of this capability into tools/processes for rapid

well design, planning, and cost estimating. Although building a MEM requires investment and one is not always available, the use of MEMs is gaining popularity and proving to add value. This is especially true for some of the major capital projects in more challenging and high-cost drilling environments. Additionally, computing power and the ability to create MEMs has improved significantly, with an associated decrease in time and cost.

As is typical of such endeavors, the existing literature was reviewed, various experts consulted, and processes used by suppliers were reviewed. EPTC, as well as other operators and bit suppliers, had some capability in this regard, but it was thought there was still considerable inaccuracies, subjectivity, or extensive local calibration required in the existing processes. EPTC concluded that the industry lacked a relatively accurate, simple, and intuitive method that is based on first principals for calculating the apparent rock strength to the bit. EPTC also concluded that the need for this method was fundamental to the attainment of its project objectives. The EPTC Rock Mechanics team, consisting of rock mechanics, drilling engineers, and earth scientists, worked to develop a simple, robust, and globally applicable solution for apparent rock strength (to the bit), and bit performance prediction methods based on this solution. The solutions that were developed combined some fundamental and innovative rock mechanics principles while leveraging and expanding upon the existing knowledge base already documented in the literature.

The Current (and Problematic) State

The industry has widely adopted the practice of using UCS for bit selection and performance prediction. This practice may be suitable for porous/permeable rock drilled with clear fluids (no wall cake), but this environment represents only a small fraction of the rock drilled by the industry. This approach is erroneous for porous/permeable rock drilled with mud, as well as for impermeable rock drilled with any type of drilling fluid. Many of those specializing in bit design and performance prediction understand the effect of confining pressure to increase the apparent strength of the rock. As such,

many have developed algorithms based on UCS, other rock properties, mud pressure, pore pressure, mud properties and so forth, and some of these are well documented in the literature. Drawbacks to this approach, however, are that the algorithms are sensitive to lithology and to other downhole environmental factors, and they are not necessarily globally applicable, intuitive, or easy to calibrate.

There is a well documented and widely accepted method for calculating rock CCS based on rock UCS, confining stress, pore pressure, and rock internal angle of friction. The technique is a common rock mechanics approach. This CCS approach can provide a more realistic representation of apparent rock strength to the bit than UCS, yet its use is still very limited. It is also somewhat flawed for impermeable rock. Its effective use is largely limited to bit performance specialists who are willing to acquire the data necessary to calculate it and who understand its shortcomings.

Several bit suppliers have implemented methods for calculating and using a confined compressive strength. These methods, however, are either erroneous, proprietary and thus limited in availability, lacking robustness for global application without calibration, or lacking intuitive simplicity based on first principles.

The Bottom Hole Environment

Figure 1 provides a general depiction of the bottom hole environment for a vertical well in porous/permeable rock.

Rock, and associated overburden stress, has been replaced by the drilling fluid. Although there can be exceptions, the pressure exerted by the drilling fluid is typically greater than pore pressure and less than overburden. Under this common drilling condition, the rock expands slightly at the bottom of the hole because of the reduction of stress (pressure from drilling fluid is less than pressure exerted by overburden). If the rock is porous, there will be an immediate pore pressure reduction in the expanded rock.

If the rock is permeable, the pore pressure reduction results in fluid movement from the far field (reservoir) into the expanded region. The rate and degree to which pore fluid flows into the expanded region, equalizing the pore pressure of the expanded region to that of the far field (reservoir pressure), is a function of a number of factors. These factors are primarily the rate of rock alteration (correlative to rate of penetration) and the relative permeability of the rock to the pore fluid (assuming that the reservoir volume is relatively large compared to the depth of cut region). At the same time, if the drilling fluid pressure is greater than the in-situ pore pressure, filtrate from the drilling fluid will enter the permeable pore space in the depth of cut zone. The wall cake built during the initial mud invasion (sometimes referred to as spurt loss) acts as a barrier to further filtrate invasion. If the wall cake buildup is efficient (very

thin and quick, which is desirable and often achieved), the impact of filtrate invasion on the pore pressure in the depth of cut zone is negligible. The mud filter cake acts as an impermeable membrane for the typical case of mud pressure being greater than pore pressure. Therefore, for highly permeable rock drilled with mud, the pore pressure in the depth of cut zone can reasonably be assumed to be essentially the same as the in-situ pore pressure.

For impermeable rock (such as shale and very tight non-shale), insignificant pore fluid movement or filtrate invasion occurs in the depth of cut zone. Therefore, the instantaneous pore pressure change in the depth of cut zone is a function of the stress change, rock properties, and in-situ pore fluid properties (primarily compressibility).

The Solution

As mentioned above, there is a widely practiced and accepted rock mechanics method for calculating CCS of rock. It is as follows:

$$CCS = UCS + DP + 2DP\sin FA / (1 - \sin FA) \quad (1)$$

where: UCS = rock unconfined compressive strength
 DP = differential pressure (or confining stress)
 FA = rock internal angle of friction

The adaptation of this method to the bottom hole drilling condition for permeable rock is accomplished by defining differential pressure as equivalent circulating density minus in-situ pore pressure. This adaptation results in the following:

$$CCS_{DP} = UCS + DP + 2DP\sin FA / (1 - \sin FA) \quad (2)$$

where: DP = ECD pressure – pore pressure (3)
 ECD pressure = pressure exerted by drilling fluid under circulating condition

For the case of impermeable rock and a vertical well, a relationship described by Skempton⁽¹⁾ was applied as a means of calculating the pore pressure at the bottom of the hole. This application results in the following:

$$CCS_{Sk} = UCS + DP_{Sk} + 2(DP_{Sk})\sin FA / (1 - \sin FA) \quad (4)$$

where: DP_{Sk} = ECD pressure – Skempton Pore Pressure (5)
 $Skempton$ Pore Pressure = $PP - (OB - ECD) / 3$ (6)

The fundamentally correct way to think about Skempton pore pressure (see Skempton Pore Pressure section) is that it is the in-situ pore pressure modified by the pore pressure change as a result of the change in average stress. In the case of a vertical well and most shale (not unusually hard and stiff), the change in average stress on the hole bottom can be approximated by “(OB-ECD)/3”. For a deviated well, the earth stress that existed normal to the bottom of the hole and prior to

the existence of the hole is substituted for overburden (OB) in the equations above. This calculation and substitution is easily implemented by any wellbore stability software.

The two solutions above, "CCS_DP" and "CCS_Sk," are considered to be endpoints. A technique of mixing (or interpolating) between the two endpoints was devised to address the intermediate permeability between essentially impermeable rock and highly permeable rock. The ChevronTexaco log-based approach to rock mechanical properties does not typically include a permeability function, but it does include effective porosity. Although there are exceptions, EPTC believed that effective porosity would most often correlate with permeability and, therefore, effective porosity could be used to quantify the permeable and impermeable end-points. The following methodology was employed to calculate CCS_Mix, the apparent confined compressive strength of the rock to the bit:

$$\begin{aligned}
 & \text{CCS_MIX} = \\
 & \text{CCS_DP if } Phie \geq .20, \\
 & \text{CCS_Sk if } Phie \leq .05, \\
 & \text{CCS_DP}(Phie-.05)/.15 + \text{CCS_Sk}(.20-Phie)/.15 \\
 & \text{if } .05 < Phie < .20. \quad (7) \\
 & \text{where: } Phie = \text{effective porosity}
 \end{aligned}$$

The previous equations are based on the assumption that the rock would behave as impermeable if $Phie$ were less than or equal to 0.05 and as permeable if $Phie$ were greater than or equal to 0.20. The endpoint $Phie$ values of 0.05 and 0.20 are assumed. Reasonable endpoints for this method are dependant upon a number of factors, including the drilling rate. $Phie$, effective porosity, is defined as the porosity of non-shale fraction of rock multiplied by the fraction of non-shale rock. Effective porosity of the shale fraction is assumed to be zero.

Validation

Validation is presented from two standpoints: lab/research data and field data.

Warren and Smith⁽²⁾ documented the results of finite element modeling of the bottom of the hole. This work confirmed that the effective stress on the bottom of the hole for permeable rock is essentially equal to the difference between mud pressure and in-situ pore pressure, except for very minor differences caused by the bottom hole profile and larger differences near the diameter.

Figure 2 illustrates the difference between mud pressure and the altered pore pressure (in the expanded depth of cut zone) for a given set of conditions for impermeable rock. This figure shows differential pressure curves calculated by Warren and Smith, as well as the simplified Skempton method. The Warren and Smith results are for a case in which overburden equals 10,000 psi, horizontal stress equals 7,000 psi, and pore

pressure equals 4,700 psi. Warren and Smith results are for 0.11 in. below the bottom of the borehole surface, and at various radial positions from the center of the hole. Additional rock properties, pore fluid properties, and bottom hole profile were required for the Warren and Smith finite element analysis. There is a fair degree of correlation between the more rigorous modeling of Warren and Smith and the simplified method presented in this paper. It should be noted that the Warren and Smith method modeled a very hard, stiff shale; the correlation would be closer for a more typical shale. The apparent difference between the two methods decreases as mud pressure increases above in-situ pore pressure. Consequently, the simplified method may be suitably accurate for the more typical over-balanced conditions, becoming less accurate as balanced conditions are approached. Regarding the discrepancy near the hole center and the diameter (edge effect), a correction for these, if required, could be easily implemented in the simplified Skempton method. Hole profile and edge effect is explained in more detail in the Limitations section.

A great deal of lab test data indicates the effect of mud confining pressure on the drill rate of rock samples. If rock properties and confining stress are known, the CCS of the rock can be calculated for each test condition. Rate of penetration (ROP) vs. CCS can then be plotted to establish the relationship between ROP and CCS. Figure 3 provides an example, using data from Cunningham and Eenink⁽³⁾. The ROP vs. CCS curve in Figure 3 is typical and our data from numerous drilling operations around the world supports the power function as being the best generalized function. For the specific test data shown in Figure 3, a power law trend line is matched and the resulting formula is indicated in Figure 3. The ROP formula shown in Figure 3 is specific to the lab 1.25-in. micro-bit and drilling parameters (weight on bit, rpm, and flow rate).

Using the ROP vs. CCS relationship from Figure 3, one can then test the presented methodology on hypothetical cases, as shown in Table 1, Figure 4, and Figure 5. This data and Figures 4 and 5 indicate that the use of absolute ECD pressure for calculating confined compressive strength yields unrealistically high values of CCS and produces no or very little ROP response. This finding is inconsistent with actual field experience. The ROP response based on CCS calculated from straight differential pressure or Skempton based differential pressure yields more realistic results than CCS calculations that are based on absolute ECD pressure.

Figure 6 illustrates an actual field application. This figure is a Rock Mechanics and Drilling Performance log from a well in the Gulf of Mexico. Tracks 1, 2, and 3 contain some of the log and calculated data used to determine rock properties. Track 4 contains the pore pressure, ECD, and overburden data in units of ppg-equivalent mud density. Track 5 contains actual surface

rate of penetration (SROP) in feet per hour and a calculated rate of penetration based on CCS_Mix. Track 6 contains the UCS and CCS described in this paper, and compares CCS_Mix to CCS_DP and CCS_Sk. Track 7 contains general bit run information. What is noteworthy is the correlation between calculated ROP and actual ROP. Also noteworthy is that the calculated ROP is with one of EPTC's global algorithms using only CCS_Mix as an input, without any calibration, and that the actual ROP appears to be more correlative to CCS_Mix than either CCS_DP or CCS_Sk alone. This is only one example of many cases in which the CCS_Mix calculation combined with ChevronTexaco global ROP algorithms provided reasonably accurate results. The CCS_Mix calculation also helps to explain the observed bit performance, whereas the UCS alone would be clearly inadequate.

Limitations

The simplified method presented in this document does not take into account the effect of a non-flat hole bottom (profile) or the effect of stress concentrations that occur near the diameter of the hole (edge effect). Rather, the simplified approach described in this paper treats the depth of cut zone across the entire hole bottom as one element in which one of three independent orthogonal stresses has been changed and the other two have not (see Figure 7). The one stress assumed to be changed is the one acting normal to the bottom of the hole and the change is represented by the difference between earth stress acting normal to bottom of the hole and mud pressure. The analogy is a cube with three independent orthogonal stresses acting normal to the sides of the cube, and then changing just one of those stresses while holding the other two constant (see Figure 7).

Profile and edge effects can be described by considering the classic example of a vertical well in which the mud pressure is significantly less than overburden, and earth principle horizontal stresses are equal and less than overburden. It is common for the center of the hole bottom to be slightly raised and either cone- or dome-shaped. The height of the cone/dome is minimal to non-existent with roller cone bits and can be more pronounced with fixed cutter bits (such as PDC, Diamond, and Impregnated bits). As the cone/dome increases in height (or more correctly, as the side slopes or aspect ratio of the cone/dome increase), the dominant confining stress will transition from earth horizontal stress (for a flat bottom) to mud pressure. For example, consider a very pointed cone with a shape similar to that of the point of a pencil. Obviously, the influence of any earth stress at the tip is essentially non-existent; the tip will be under the stress of the mud pressure and nothing else. The influence of earth stresses will be nonexistent to very low from the tip to near the base of the cone, at which point earth stress would start to influence.

Immediately inside the diameter of the borehole, earth stress acting on the rock has been replaced by mud pressure. Immediately outside the diameter, overburden is still acting as the vertical stress. Some of the stress in the higher stressed region (just outside the diameter) is transferred to the lower stressed region (just inside the diameter). The result is less rock expansion and less pore pressure decrease near the diameter.

Warren and Smith describe the 3D nature of the bottom of the hole and the results of their 3D finite element analysis⁽²⁾. The difference between the Warren and Smith model and the simplified method is depicted in Figure 2. In Figure 2, the Warren and Smith curve for $P_{well}=6,700$ psi clearly indicates hole profile and edge effects. It is encouraging that our proposed methodology forms an approximate correlation to the more rigorous analysis of Warren and Smith. Figure 2 should not be used as an indication of the amount of error in general. The curves of the Warren and Smith model are for rock that is relatively stiff and, because most shales are less stiff, the error would be less. Further, the potential error arising from not taking into account hole profile and edge effect is likely to be relatively constant over varying influences. Consequently, to the extent that bit performance predictive models are calibrated to the simplified CCS methodology, the error arising from not rigorously modeling the bottom hole profile and 3D stresses may be inconsequential.

Two dominant bottom hole conditions influence bit performance: the condition of the rock immediately below the bit and the condition of the rock as it is removed by the bit. These conditions were acknowledged by Warren and Smith⁽²⁾ when they state, "The causes of the reduction in ROP with depth can be divided into two general categories: (1) processes that affect the unbroken rock, and (2) processes that act on the rock once it is broken into chips." The basis for the methodology presented in this document is that the condition of the rock below the bit represents both a fundamental influence and the starting point for modeling, and it is the condition of the rock below the bit that the proposed solution targets. This does not imply that the dynamic changes that occur in the rock as it is deformed by the bit are not significant. These changes can sometimes be significant secondary factors and, when so, must be considered.

FA may change as confining stress changes. This is because of what rock mechanics refer to as a curved failure envelope. The net effect that must be understood is that at high confining stress (>5,000 psi), some rocks exhibit a declining rate of increase in confined strength as confining stress increases, and some reach a peak confined strength that does not increase with further increase in confining stress. This condition would obviously present error to the methodology presented in this paper if FA is taken as a constant. The degree to which FA changes as confining stress changes varies

with rock type and with rock properties within a type. When the change in FA with change in confining stress is significant, then FA should be modified to be a function of the confining stress.

The method does not require lithology. For bit selection or bit performance modeling, lithology is commonly a required specification to those skilled in the art. The methodology presented in this paper is based on the assumption that UCS and FA represent the dominant influencing rock properties and, therefore, lithology specification is not required. More experience is required to confirm a high confidence level of this approach. Although lithology is not needed for bit selection and performance modeling with the proposed method, it may be required if FA varies significantly with confining stress.

Rock stiffness, porosity, and pore fluid compressibility influence the amount of pore pressure change that occurs when impermeable rock expands. The simplistic model presented in this paper for impermeable rock does not take those factors directly into account. They can be accounted for by the Skempton "B" coefficient, which is explained in more detail in this document. The error will be relatively small whenever rock compressibility is significantly greater than pore fluid compressibility, and this is the case for most shales (which are not hard and stiff and contain water as the pore fluid). The error may become significant for shale that is hard and stiff, and is very likely for very tight and stiff carbonates. In this case, both the pore pressure drop and differential pressure will be over-predicted. This error can be removed by adjusting the "B" coefficient to account for rock stiffness, and if necessary, porosity and pore fluid compressibility.

Rock can sometimes exhibit anisotropic properties; that is, having one or more physical properties that vary with direction. Shale is typically anisotropic as a result of bedding planes. The simplified model presented herein does not take anisotropy into account. Strength anisotropy is typically significant only for old and highly compacted hard shales and highly fissile shales. Although young soft shales have significant anisotropy to the eye, they don't have significant strength anisotropy. The potential error due to any mechanical property anisotropy is largely within the uncertainty of the mechanical property estimates for most rocks, and can be ignored except for old highly compacted hard shales and highly fissile shales.

Some of the literature presents evidence that apparent rock strength (or rock behavior) to the bit in certain shale may be more a function of absolute ECD pressure than a difference in ECD pressure and pore pressure⁽⁴⁾. These are well-founded claims. There are likely reasonable explanations for any apparent or real difference, such as this phenomena being more related to the cuttings behavior, rather than to the apparent strength of the rock at the bottom of the hole. The

influence of cuttings behavior can be managed by proper bit design and hydraulics, and the performance of a properly designed and operated bit will then be more a function of apparent rock strength and operating parameters than cuttings behavior. Our experiences to date on numerous wells throughout the world suggest that this is the case.

Skempton Pore Pressure

Skempton⁽¹⁾ describes the two pore pressure coefficients A and B, which determine the change in pore pressure caused by changes in applied total stress, for a porous material under conditions of zero drainage. The change in pore pressure, ΔPP , is given by:

$$\Delta PP = B[(\Delta\sigma_1 + 2\Delta\sigma_3)/3 + (\Delta\sigma_1 - \Delta\sigma_3)*(3A - 1)/3] \quad (8)$$

This equation is written for the case in which σ_2 is always equal to σ_3 , so σ_3 in the equation represents both σ_2 and σ_3 . Thus, $(\Delta\sigma_1 + 2\Delta\sigma_3)/3$ represents the change in average, or mean, stress, and $(\Delta\sigma_1 - \Delta\sigma_3)$ represents the change in shear stress.

For an elastic material, it can be shown that $A=1/3$. This is because a change in shear stress causes no volume change for an elastic material. If there is no volume change, then there is no pore pressure change (the pore fluid neither expands nor compresses). If we assume that the rock near the bottom of the hole is deforming elastically, then we can simplify the pore pressure change equation to:

$$\Delta PP = B(\Delta\sigma_1 + 2\Delta\sigma_3)/3 \quad (9)$$

For the case of three independent orthogonal stresses, this equation can be re-written as:

$$\Delta PP = B(\Delta\sigma_1 + \Delta\sigma_2 + \Delta\sigma_3)/3 \quad (10)$$

This equation states that pore pressure change is equal to the constant B multiplied by the change in mean, or average, total stress.

Note that mean stress is an invariant property. It is the same regardless of which coordinate system is used. Thus, the stresses do not need to be principal stresses. The equation is accurate as long as the three stresses are mutually perpendicular. For convenience, we can define σ_z as the stress acting in the direction of the wellbore and rewrite the equation as:

$$\Delta PP = B(\Delta\sigma_z + \Delta\sigma_x + \Delta\sigma_y)/3 \quad (11)$$

There will be changes in σ_x and σ_y near the bottom of the hole. However, these changes are small and can be neglected for a simplified approach. The equation then simplifies to:

$$\Delta PP = B(\Delta\sigma_z)/3 \quad (12)$$

For most shales, the value of B is between 0.8 and ~1.0. Young, soft shales have B values of 0.95 to 1.0, while older, stiffer shales will be closer to 0.8. For a simplified approach that does not require rock properties, we assume B=1.0. Because $\Delta\sigma_z$ is equal to $(ECD - \sigma_z)$, we can rewrite the equation as:

$$\Delta PP = (ECD - \sigma_z)/3 \quad (13)$$

Note that ΔPP is almost always negative. That is, there will be a pore pressure decrease near the bottom of the hole. This is because ECD is almost always less than all the in-situ stresses.

The altered pore pressure near the bottom of the hole is equal to $PP + \Delta PP$, or $PP + (ECD - \sigma_z)/3$. This can also be expressed as $PP - (\sigma_z - ECD)/3$. For the case of a vertical well, σ_z is equal to the overburden stress (OB).

If the formation has a B value that is less than one, then the error caused by assuming B=1 will cause a slight over-prediction of the amount of pore pressure decrease. This over-prediction is evident in Figure 2. In this figure, the Warren and Smith results⁽²⁾ are for a shale that is extremely hard and stiff (B = 0.57). For a more typical shale B value, their calculated differential pressure values would be approximately 500 psi higher, which would correlate extremely well with our simplified Skempton calculation. A more robust application of this Skempton-based approach would be to calculate an approximate B value based on log-derived rock properties, and also to account for changes in σ_x and σ_y , if necessary.

For the case of a very stiff, but very low-permeability rock, such as a very tight carbonate, B is likely to be much less than 1.0 and could easily be on the order of 0.5. The actual value of B should, therefore, be taken into account for tight non-shale lithologies. Extremely stiff shales may also require adjustment of the B value.

If the stress change that occurs near the bottom of the hole is enough to cause non-elastic behavior (because of increasing shear stress), this can be accounted for by using the appropriate value of A, instead of assuming A=1/3. In a more advanced approach, the A term can also be used to represent instantaneous pore pressure changes that occur in the rock as it is being cut and failed by the bit. These pore pressure changes are a function of whether the rock is failing in a dilatant or non-dilatant manner, and can also exhibit strain-rate effects at high strain rates (such as Cook, et. al. For additional information, see the References section.).

Deviated Well

In the case of a deviated well, the earth stress that existed normal to the bottom of the hole and prior to the existence of the hole is substituted for overburden (OB) in the equations above. The earth stress that existed

normal to the bottom of the hole is a component of overburden and horizontal stresses. Earth horizontal stress is typically characterized as two principal horizontal stresses. Earth principal horizontal stresses are typically less than overburden, except in the existence of tectonic force, which can cause the maximum principal horizontal stress to be greater than overburden. For competent rock in a non-tectonic environments, horizontal effective stress is typically on the order of 1/4 to 3/4 of effective overburden stress. In very pliable and/or plastic rock, however, the effective horizontal stress can approach or equal overburden. Figure 7 illustrates several wellbore orientations and the appropriate stresses acting on an element of the bottom of the hole. It should be noted that these are also simplified, ignoring hole profile, edge effect, and the true 3D nature of bottom hole stresses.

Conclusions

1. The use of UCS for bit selection, bit performance prediction, and bit performance analysis is problematic, especially for cases involving significant overbalance and deep drilling of shale and tight non-shale rock.
2. A methodology has been developed for the calculation of an apparent confined compressive strength (CCS) of the rock to the bit. This methodology has removed much uncertainty and subjectivity regarding the apparent strength of the rock to the bit, bit selection, and bit performance modeling, especially in deep and/or significantly over-balanced drilling conditions.
3. The method is simple yet robust, globally applicable, based on fundamental and/or first principles, and requires little or no calibration. Any calibration required is simple and intuitive.
4. The CCS method requires rock unconfined compressive strength (UCS), rock internal angle of friction (FA), overburden (OB), pore pressure (PP), and equivalent circulating density (ECD). UCS and FA are common to current day processes in use by bit suppliers and bit performance specialists, and OB, PP, and ECD are typically known for well design. Thus, the required inputs are commonly available. For the case of a highly deviated well (>30 degrees), well deviation, azimuth, and earth principle horizontal stresses may be required for improved accuracy. These inputs, if required, are common to wellbore stability software.
5. The method has been implemented by ChevronTexaco in conjunction with new rate of penetration prediction models.
6. The new method has proved valuable, improving drilling performance and reducing well cost by improving bit performance prediction, bit selection, and determination of optimum drilling parameters.

Nomenclature

A	= Skempton coefficient, dimensionless
B	= Skempton coefficient, dimensionless
CCS_{DP}	= DP Confined Compressive Strength, psi, based on DP
CCS_{CCS_ECD}	= Confined Compressive Strength, psi, based on DP_ECD
CCS_{Sk}	= Confined Compressive Strength, psi, based on DP_Sk
DP	= (ECD pressure – PP), psi
DP_ECD	= ECD pressure, psi
DP_Sk	= ECD Pressure – Skempton Pore Pressure, psi
ECD	= Equivalent Circulating Density, ppg
$ECD\ Pressure$	= pressure in psi exerted by an ECD
FA	= Rock Internal Angle of Friction, degrees
OB	= Overburden, psi or ppg
$Phie$	= Effective Porosity (porosity of non-shale fraction of rock multiplied by the fraction of non-shale rock), Volume per Volume, "fraction", or percent
PP	= pore pressure, psi or ppg
ppg	= pounds per gallon
ROP_{DP}	= Rate of penetration, ft/hr, based on CCS_{DP}
ROP_{Sk}	= Rate of penetration, ft/hr, based on CCS_{Sk}
ROP_{ECD}	= Rate of penetration, ft/hr, based on CCS_{ECD}

UCS = Rock Unconfined Compressive Strength, psi

$\Delta\sigma_1, \Delta\sigma_2, \Delta\sigma_3$ = changes in the three principle orthogonal stresses

$\Delta\sigma_x$ = change in bottom hole stress normal to axis of wellbore, psi

$\Delta\sigma_y$ = change in bottom hole stress normal to axis of wellbore, psi

$\Delta\sigma_z$ = change in bottom hole stress parallel to axis of wellbore, psi

ΔPP = change in pore pressure, psi or ppg equivalent

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Table 1. Calculated values of differential pressure, confined compressive strength, and rate of penetration

Depth	PP	OB	ECD	UCS	FA	CCS_DP	CCS_Sk	CCS_ECD	ROP_DP	ROP_Sk	ROP_ECD	DP	DP_Sk	DP_ECD
10,000	9	18	9	5,000	25	5,000	8,839	16,518	73.2	34.3	15.0	0	1,558	4,675
10,000	9	18	10	5,000	25	6,280	9,692	17,798	54.1	30.4	13.6	519	1,904	5,194
10,000	9	18	11	5,000	25	7,560	10,546	19,077	42.3	27.2	12.4	1,039	2,251	5,713
10,000	9	18	12	5,000	25	8,839	11,399	20,357	34.3	24.5	11.3	1,558	2,597	6,233
10,000	9	18	12	5,000	25	8,839	11,399	20,357	34.3	24.5	11.3	1,558	2,597	6,233
10,000	9.5	18	12	5,000	25	8,199	10,759	20,357	37.9	26.4	11.3	1,299	2,337	6,233
10,000	10	18	12	5,000	25	7,560	10,119	20,357	42.3	28.7	11.3	1,039	2,078	6,233
10,000	10.5	18	12	5,000	25	6,920	9,479	20,357	47.5	31.3	11.3	779	1,818	6,233
10,000	11	18	12	5,000	25	6,280	8,839	20,357	54.1	34.3	11.3	519	1,558	6,233

Depth, feet

PP = pore pressure, ppg

OB = Overburden, ppg

ECD = Equivalent Circulating Density, ppg

UCS = Unconfined Compressive Strength, psi

FA = Friction Angle, degrees

CCS_DP = Confined Compressive Strength, psi, based on DP

CCS_Sk = Confined Compressive Strength, psi, based on DP_Sk

CCS_ECD = Confined Compressive Strength, psi, based on DP_ECD

ROP_DP = Rate of penetration, ft/hr, based on CCS_DP

ROP_Sk = Rate of penetration, ft/hr, based on CCS_Sk

ROP_ECD = Rate of penetration, ft/hr, based on CCS_ECD

DP = (ECD – pore pressure), psi

DP_Sk = [ECD – {PP-(OB-ECD)/3}], psi

DP_ECD = ECD pressure, psi

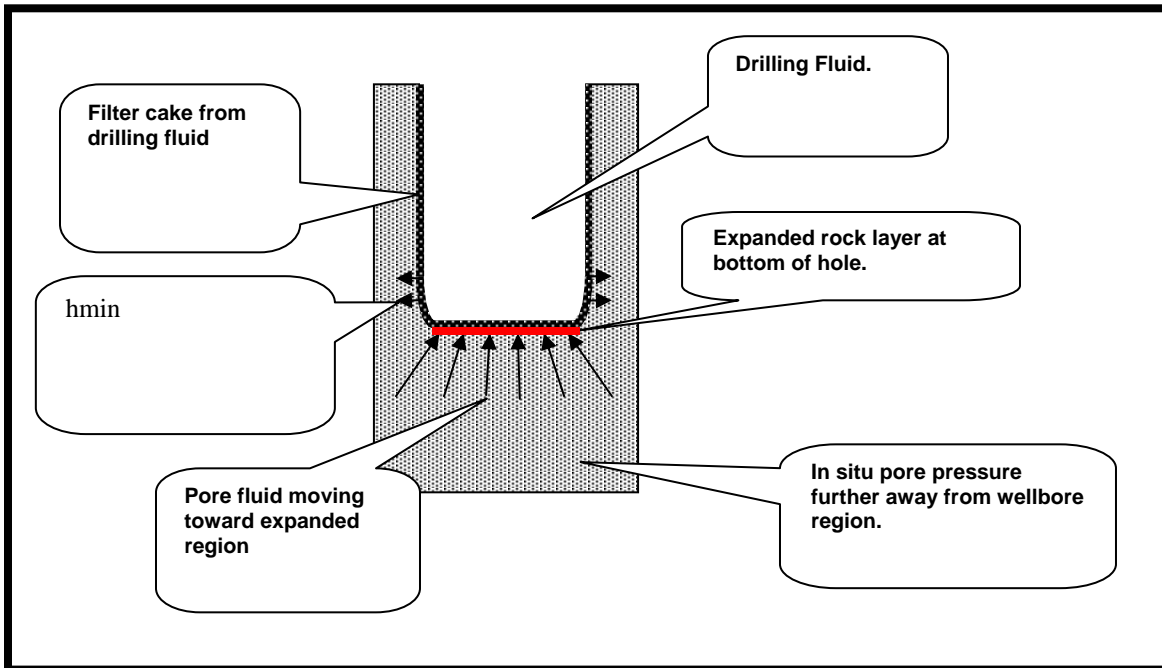


Figure 1. Bottom hole environment for a vertical well in porous/permeable rock.

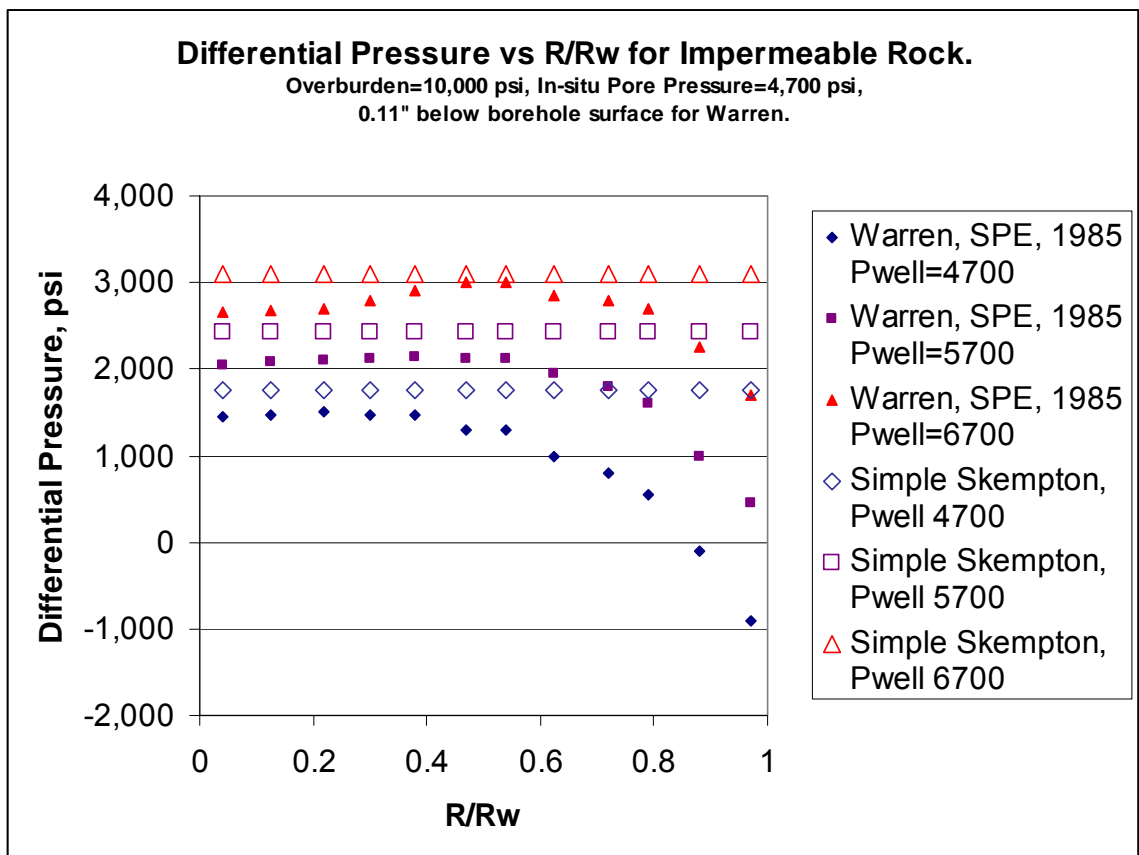


Figure 2. Differential pressure at bottom of hole for impermeable rock (comparison of simplified Skempton method and results reported by Warren and Smith²).

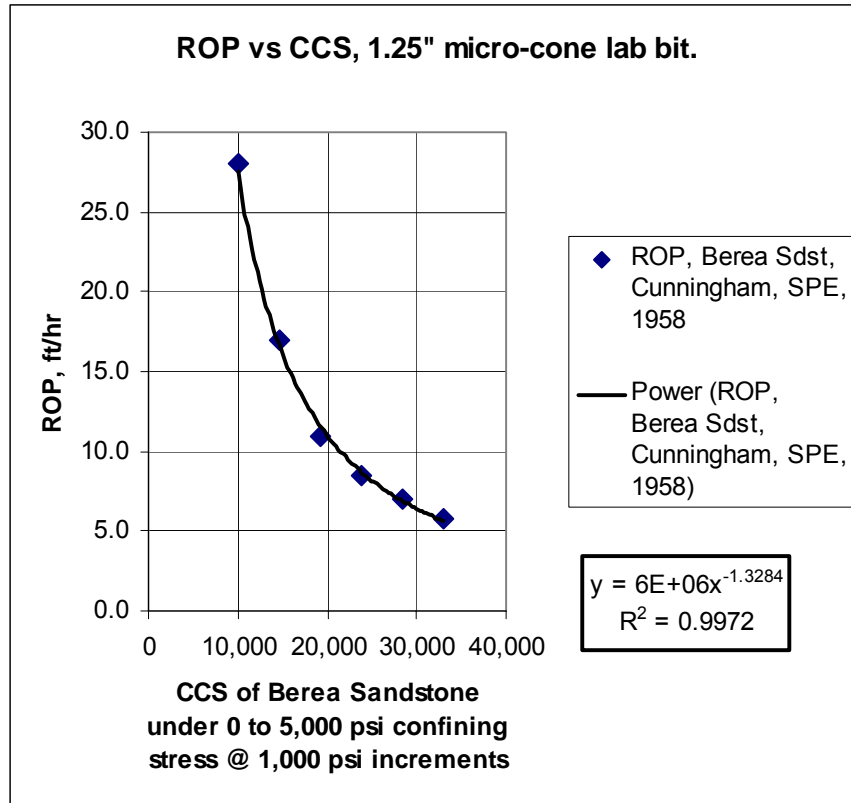


Figure 3. ROP vs CCS for 1.25-in. micro-bit in lab. ROP data from Cunningham, SPE, 1958.

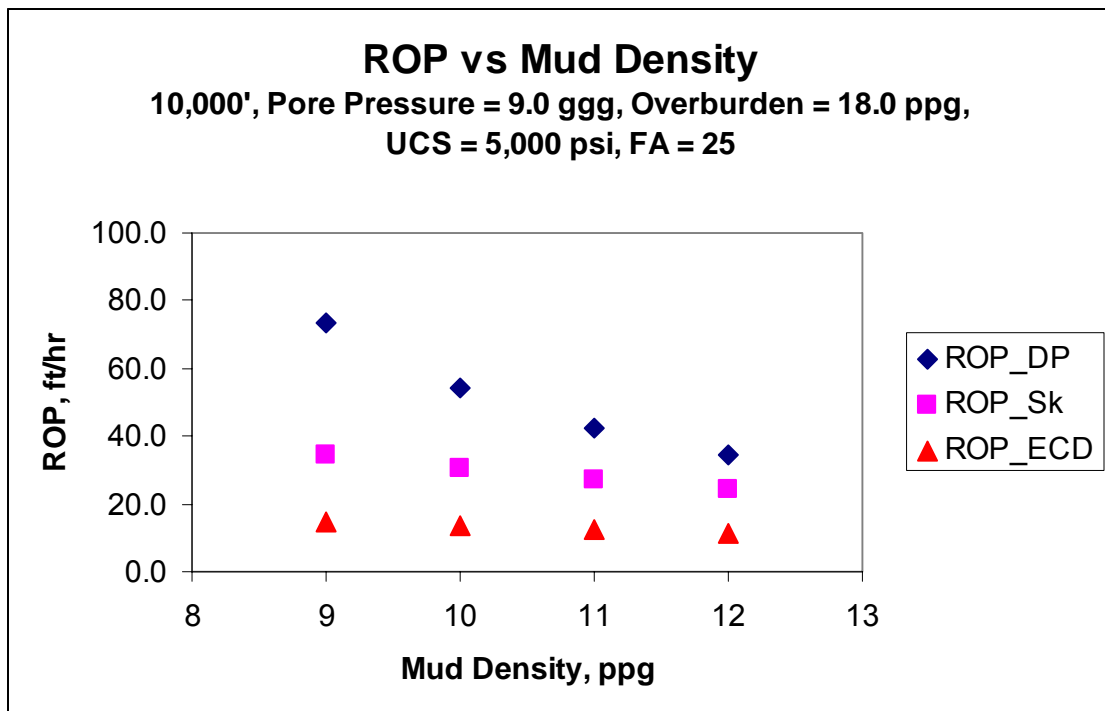


Figure 4. ROP vs Mud Density, constant pore pressure, three methods of calculating CCS - CCS_DP, CCS_Sk, and CCS_ECD.

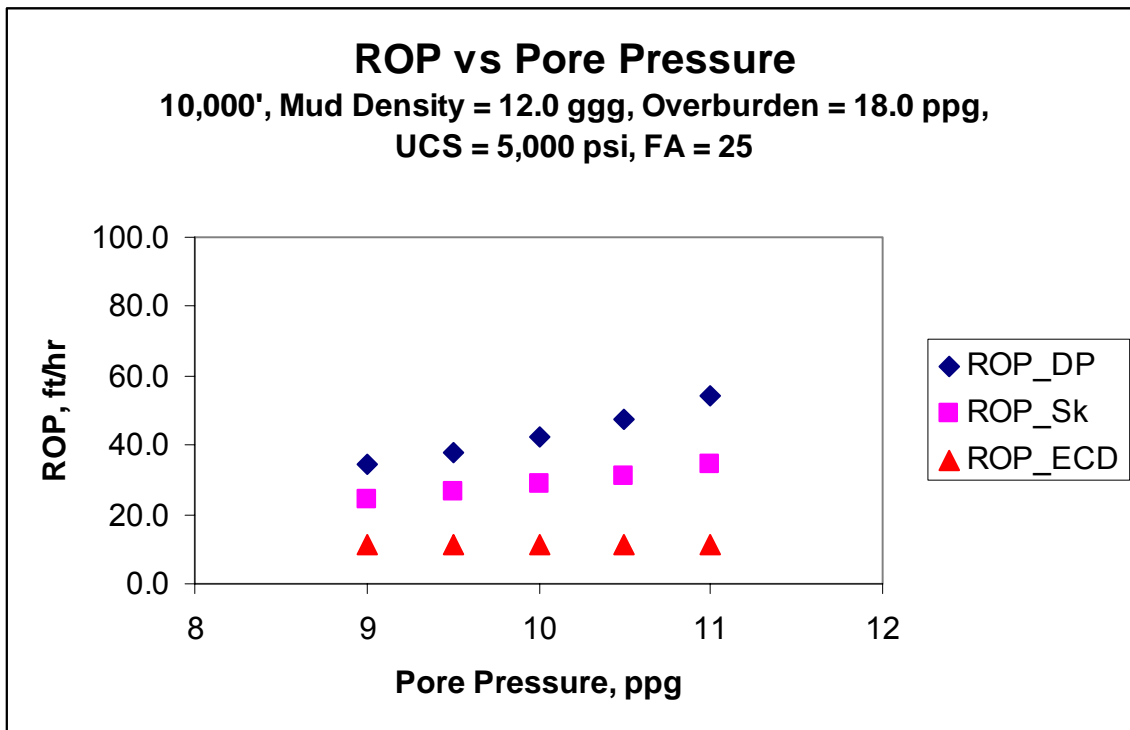


Figure 5. ROP vs. pore pressure, constant mud density, three methods of calculating CCS - CCS_DP, CCS_Sk, and CCS_ECD.

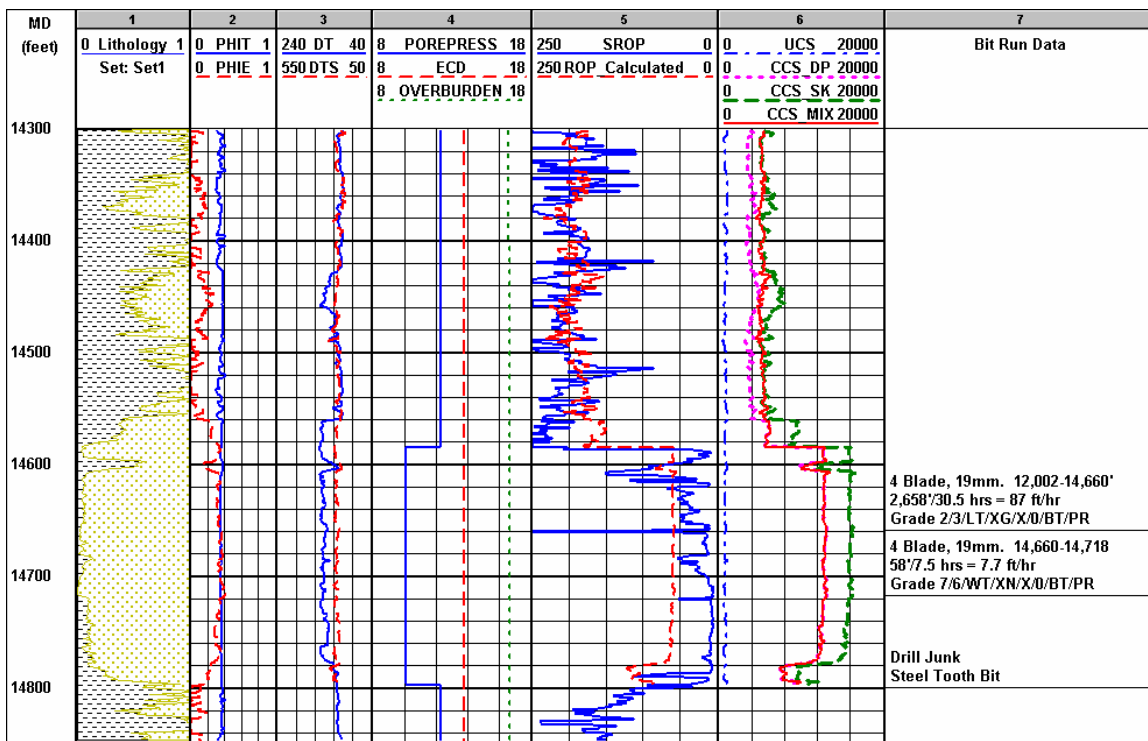


Figure 6. Rock Mechanics and Drilling Performance log from a well in the Gulf of Mexico.

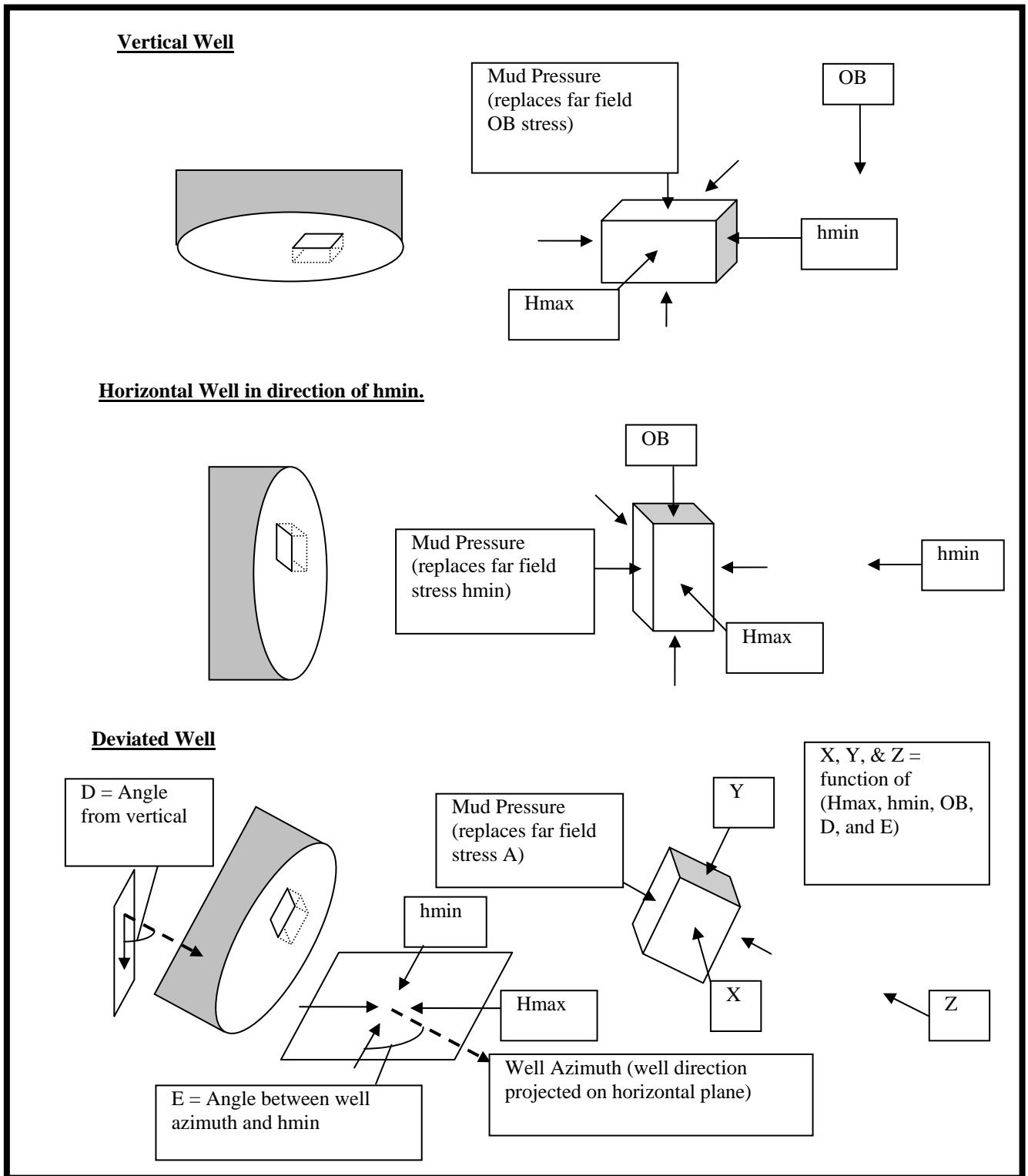


Figure 7. Simplified depiction of stresses and stress changes on element of bottom of hole for various wellbore orientations.