ROCK MECHANICAL MODELLING FOR A UNDERBALANCED DRILLING RATE OF PENETRATION   PREDICTION

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ABSTRACT: Accurate knowledge of rock strength is essential for drilling optimization and rate of penetration (ROP) prediction. Conventional drilling simulators provide a tool to generate rock strength for the drilling engineer to further model and study the effect of different drilling parameters which can optimize the overall drilling process performance. Experience shows that the best correlation is generated from actual drilling data which consider the effect of drilling and bit design parameters on rock strength. The work presented herein focus on generating rock strength based on the geological and drilling data from offset wells to generate the rock strength for the underbalanced drilling (UBD) condition. The scope of the paper is divided into the following phases:

- Theoretical development of the rock strength correlation needed in the ROP modeling where both the overbalanced and underbalanced drilling condition is considered.

- Prediction of bottom hole pressure for UBD operations with aerated or foam drilling

- Correlation from the confined compressive strength (CCS) under either underbalanced or overbalanced drilling conditions to uniaxial drilling strength.

- Verification using actual drilling data to predict ROP and compare it to field data from UBD operations using the ROP models.

The application of this work links a UBD bottom hole prediction program and drilling rock strength in a ROP drill bit model, which results in a UBD drilling simulator that is a great preplanning tool for drilling engineers.

1. INTRODUCTION:

1.1. Rock Strength Confinement

Well planning by analysis of bit performance based on log-based rock strength has become standard practice in the drilling industry. There are accepted methods in the literature to calculate rock confined compressive strength (CCS) based on rock unconfined compressive strength (UCS) and pore pressure. Skempton[1] developed for impermeable rock in vertical wells a relationship described by

$$CCS = UCS + (BHP - P_p) + 2*(BHP - P_p)*\sin(\frac{Fa}{1 - \sin Fa}) \quad (1)$$

Where,

F_a =Rock internal angle of friction, degrees

P_a =Pore Pressure (psi)

BHP =Bottom Hole Pressure (psi)

Rampersad and Hareland[2] proposed the following correlation between confinement pressure "P_c "and drilling rock strength "CCS " values as

$$CCS = UCS(1 + a_s P_c^{b_s}) \quad (2)$$

Where "a_s" and "b_s" are coefficients dependent on rock permeability and type. "UCS" is the unconfined compressive strength of the rock in psi. Confinement pressure (P_c) is the pressure exerted on the rock matrix and is equal to difference of the applied external pressure (i.e. drilling mud dynamic or hydrostatic pressure) and the pore pressure of the fluid inside the rock.

1.2. Rock Strength from Sonic Log Travel Time and Drilling Data

Onyia[3] found a universal correlation between sonic logs and laboratory rock core strength tests for homogeneous and mixed lithology based on data from cored wells in Catoosa, Oklahoma as;

$$\delta_{ARS} = -3.0444 + \frac{881.1229}{\Delta t_c} \qquad (3)$$

Where, Δt_c, is the traveling time in µs/ft, and δ_{ARS} is the apparent rock strength (ARS) in psi. UCS also can be calculated from drilling data. Experiments in Catoosa, Oklahoma also showed that drilling based rock strength through inverted ROP models also gave a good method of estimating rock strength. The advantage of using drilling data is that the rate of penetration (ROP) models used takes into account operational drilling parameters, bit types/designs and geological formation information. In this paper a PDC bit ROP models was used to generate rock strength based on the geological and drilling data from an offset well which was drilled by conventional over balanced drilling method (OBD) to generate an apparent rock strength log (ARSL). Then the ARSL was used to simulate the ROP for underbalanced drilling (UBD) condition through the same formations.

2. BOTTOM HOLE PRESSURE CALCULATION

Estimation of bottomhole pressure (BHP) is one of the most important tasks during UBD. Accurate prediction of BHP is the key to successful underbalanced drilling operations. Two of the most important parameters in BHP calculation:

- Annular frictional pressure losses
- Mixture density

These are very difficult to evaluate due to multiphase flow behaviors, where gas, liquid and solids flow simultaneously with different flow rates. The following criteria are used as basic guidelines for the development of foam and aerated drilling hydraulic optimization and BHP calculation program.

1. Back pressure needs to be kept as low as possible for a convenient BHP control.
2. In UBD operations, solid concentration is preferred to be kept at less then 4%.
3. Bottom hole Kinematical Energy per unit volume should be more than 3 (lb-ft/ft^3) for better cutting removal.
4. The gas and liquid volumetric flow rate needs to be kept as low as possible to reduce the cost.
5. The aerated mud velocity should not be too high to avoid the wellbore erosion.

From the first law of thermodynamics and neglecting the velocity change in a vertical conduit: The BHP including hydrostatic and frictional pressures is then solved numerically using the equation (4). After calculating the BHP at each section by considering this section temperature and related gas rate, the optimum rates for gas injection and mud rates are obtained[4].

$$\int_{P_s}^{P} \frac{\alpha P + 1}{P\left(1 + \beta\left(\frac{\gamma}{P} + \eta\right)^2\right)} dP = H \qquad (4)$$

This equation calculate pressure drop at each selected interval (H) starting from surface "P_s". α, γ, η are functions of gas, liquid, generated cutting flow rate, and annulus area. β is the function of hole size and frictional pressure. By knowing integral answer (right hand side) and its lower limit, numerical solution results in the upper limit "P" which is applied as the lower limit of next section. This process is continued and the BHP calculated for the actual field flow condition.

3. PDC BIT MODEL:

Hareland[5] proposed a model to predict ROP for PDC bits. The model was based on the conservation of mass where the rate of penetration is equivalent to the rate of rock removal from the front of the cutter. ROP was related to operational parameters by means of the rock failure criteria and geometrical relationship. The equation for ROP is presented by:

$$ROP = \frac{14.14 \cdot WOB \cdot RPM \cdot Cos\,\alpha}{CCS \cdot D_B \cdot \tan\theta} \cdot \frac{a}{RPM^b \cdot WOB^c} \qquad (5)$$

Where "D_b" is bit diameter, WOB is weight on bit, RPM is rotational speed, alpha and theta are the cutter rake angles, and "σ" is the rock strength in psi. The constants "a", "b" and "c" are bit design factors.

4. DETERMINATION OF CCS AS A FUNCTION OF BHP FOR UBD OPERATIONS

In conventional drilling, mud weight is generally selected so that hydrostatic pressure is about 200 to 1000 psi higher than pore/reservoir pressure. During UBD drilling conditions the drilling fluid typically provides a hydrostatic pressure of around 100-200 psi below the pore/reservoir pressure shown in Figure 1.
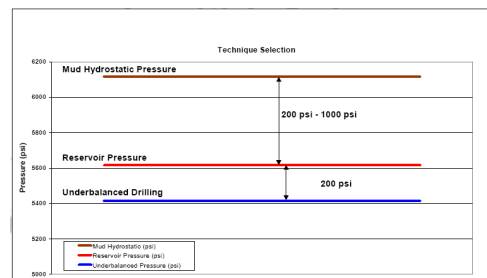

Fig1:Typical pressure range for OBD and UBD conditions

Confinement pressure (BHP-P_p) takes positive values in OBD condition and negative value when UBD is applied. Drilling rock strength (CCS) is greater than unconfined rock strength (UCS) for overbalanced drilling. The typical upper and lower limit of CCS during OBD is based on equation (2) and gives for a range of overbalance from 0 to 1500 psi that

$$1.00*UCS < CCS < 1.89*UCS \qquad (6)$$

Due to the negative effect of pore pressure on CCS in UBD operations CCS is lower than UCS. The lower limit is a function of the BHP effect on the rock face under the dril bit.

$$f(BHP)*UCS < CCS_{UBD} < UCS \qquad (7)$$

One of the most important advantages of UBD over overbalanced drilling is higher ROP due to lower BHP. In most UBD drilling literature reported data shows that three times faster ROP is achievable in UBD. Equation (5) indicates that ROP is inversely proportional to CCS. Based on the above observation of three times faster ROP (model independent assumption) means 3 times weaker confined compressive strength (model dependant assumption). This assumption is taken as one of boundary conditions to generate a new CCS correlation for UBD operations. The second boundary condition applied in generating the UBD CCS correlation is generated from the transition zone from UBD to OBD which occurs at zero confinement pressure. The slope of the CCS curve must therefore be equal on both sides. The equation (8) was generated to give the correlation between UCS, CCS, and P_c for the UBD condition. Figure 2 shows the normalized relation between Pc and CCS;

$$CCS_{UBD} = (\frac{2}{3})UCS*\exp(-a'.P_c) + (\frac{1}{3})UCS \qquad (8)$$

$$a' = 0.0033237$$

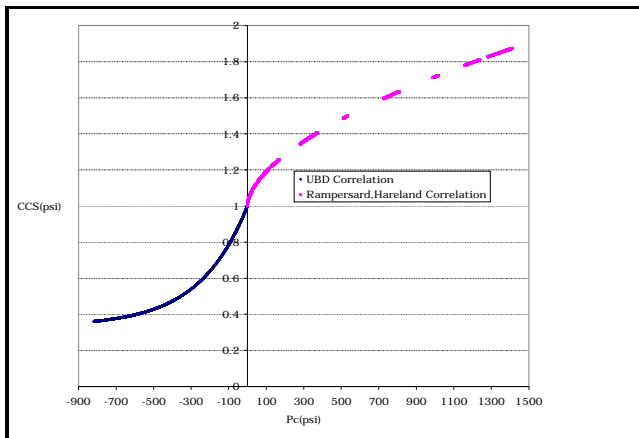

Fig 2: Normalized CCS Vs. Pc

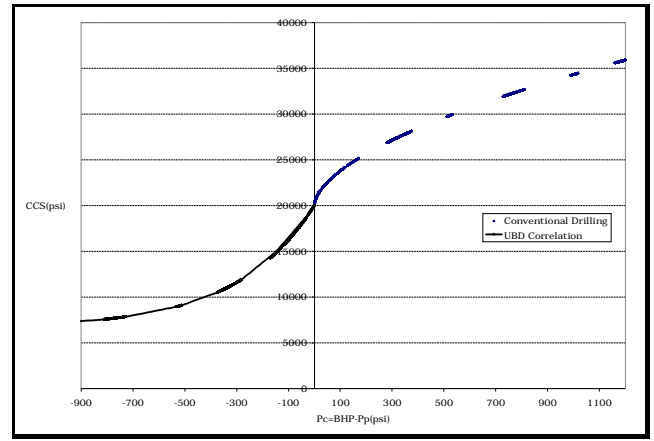Figure 3 shows the normalized effect of confinement on a 20,000 psi uniaxial compressive rock strength

Figure 3: CCS vs. Pc for 20,000 psi UCS rock

5. FIELD CASE: CALCULATION OF CCS FOR PDC BIT RUNS

Drilling data was used to derive rock strength as a function of depth for a PDC bit run using equation (9). The drilling data needed are:

- Weight on bit (WOB)
- Rotary speed RPM
- Mud weight
- Reported ROP
- Bit design and wear information

The rate of penetration model for a PDC bit also has a bit "Wear Function" which describes the wear status of the drill bit and is developed from the geometrical cutter properties and the cutter wearflat area[6];

$$ROP = W_f . \frac{14.14.WOB.RPM^b.Cos\alpha}{CCS.D_B.\tan\theta} \qquad (9)$$

Where W_f is the wear function which takes the value of 1 for a new bit or less than 1 for a PDC bit with worn cutters. Outputs of ROP and rate of wear of the drill bit is determined iteratively knowing bit wear when the bit was pulled. The drilling rock strength plots are main graphs to consider and planning and understand drilling performance.
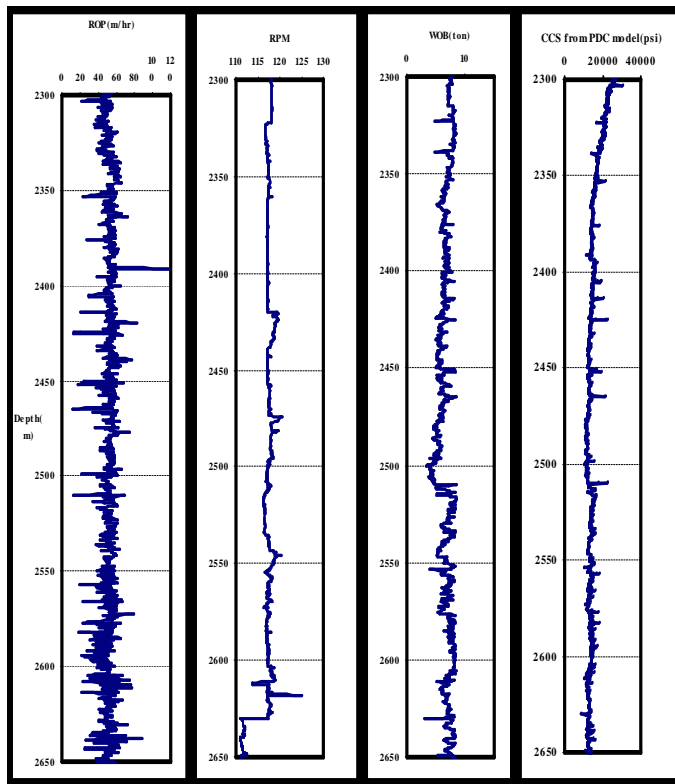
Fig 4: Generating CCS from drilling parameters (except mud weight effect)

The generated CCS in Figure 4 has integrated bit wear effects in it.

The calculated CCS (based on the correlations presented herein) and the rock strength calculated form an available drilling simulator[7] was compared as seen in Figure 5.
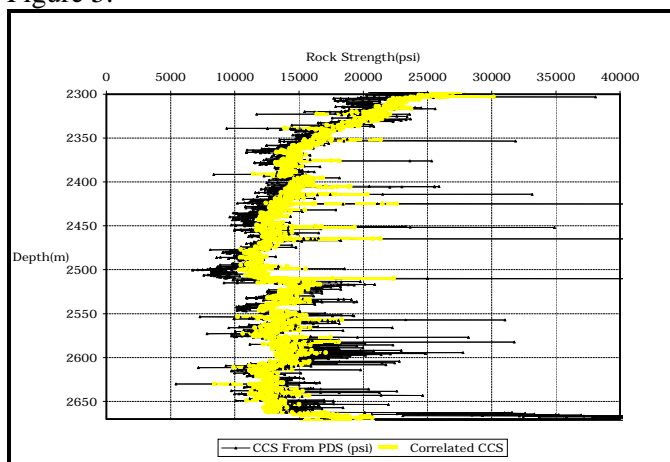

Figure 5: Compared CCS from simulator and presented method

Figure 5 shows that there is a good correlation between the ROP model and the output from a commercially available simulator which gives us the confidence that we can also use the equations for UBD drilling applications.

A planned UBD operation using BHP calculated based on minimum volumetric requirement for best cutting removal to surface for this 350m interval gives the ROP results for the same PDC bit run and is shown in Figure 6.
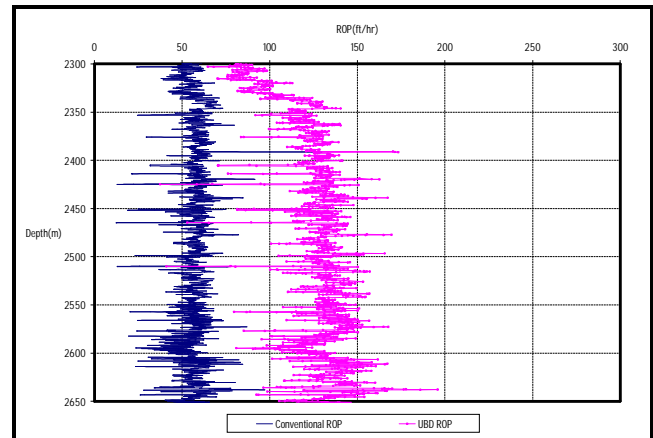

Fig 6: ROP Prediction for UBD Condition

Doing the same procedure as above for a field in Southern Iran and comparing the field UBD ROPs to the simulated ROPs for different bit runs shows good agreement in Figure 7.
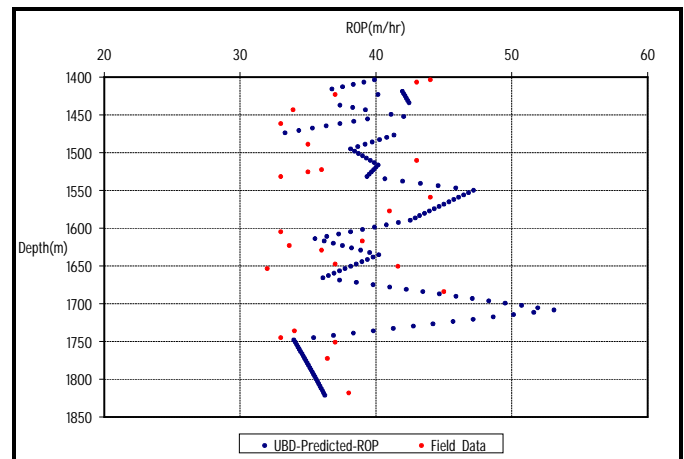

Fig 7: UBD ROP Model Validation

Conclusion:

1-A correlation was developed that account for both the conventional and UBD drilling BHP to predict unconfined rock strength and that can be used universally between the two methods of drilling.

2. The correlation can be used to predict rock strength from one type of drilling operation and applied in drilling simulation and drilling optimization of a new well planned using a different type of drilling operation.

3- The validation and accuracy of the approach has been established with comparisons to field data. More field drilling data is needed to validate the approach and model.

4. A commercially available drilling simulator was used to validate the rock strength including the mud weight effects.

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