# Effect of rocks anisotropy on deviation tendencies of drilling systems

Effet de l'anisotropie des roches sur les tendances déviationnelles des systèmes de forage pétrolier

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**ABSTRACT**. Cases history have demonstrated that inter-bedded formations are a major cause of borehole deviation and tortuosity. This phenomenon induces higher torque and drag, running tubular problems, stabilizers wear, pipe damage and trajectory controlling problems. In some fields, shale formations have a tendency to cause wellbore deviations to undesired directions. The formation anisotropy modifies the rock-bit and the bit-string interactions. Those interactions have to be fully understood in order to eliminate the undesired well deviations and tortuosities. To do so, an experimental drilling program has been carried out on a full-scale bench using various commercial drilling bits in different formations including anisotropic shale at several dip angles. Due to the limitation of the existing criterion to describe the failure of anisotropic rocks, a new criterion was developed. It introduces the notion of fictitious isotropic material obtained by using a linear anisotropic operator. Coupling a 3D bit-rock model with a 3D bottomhole assembly (BHA) model, enables to predict the occurrence of tortuosity (due to the anisotropy) at small and large scales (micro and macro-tortuosity) and to evaluate feet by feet the response of the commercial directional drilling systems (rotary, steerable motors or rotary steerable systems). A post analysis of some real drilling cases showed that, when the anisotropy of the formations is known, it is possible to select the best drilling system minimizing the well tortuosity.

## 1 INTRODUCTION

The effect of the anisotropy of drilled rock formations on deviation tendencies of drilling systems has been observed since a long time, both in laboratories and fields (Brown et al., 1981; Reich et al., 2003; Simon, 1996). In fact, field observations showed that laminated formations have caused well deviations from planed trajectories. This phenomenon is considered as problematic and costly by the drillers since it requires several correctional operations and the use of expensive directional drilling systems.

Drillers have observed that drilling through inter-bedded formations hard/soft causes inevitable and unwanted undulations around the planned well trajectory. These deviations, called tortuosity, have been recognized as one of the critical factors in extended-reach wells because they induce a high torque and drag, poor hole cleaning, drillstring buckling and running tubular problems. Tortuosity induces also BHA (Bottom-Hole Assembly) components wear. In specific applications, excessive tortuosity in horizontal wells can even impair productivity.

When drilling these anisotropic formations (laminated or inter-bedded rock), the first cause for deviation is attributed to the cutter-rock interaction hence to the drilling bit-rock interaction.

The goal of this paper is to describe a theoretical model developed and calibrated on full-scale drilling benches in order to describe those interactions and show how they can affect the directional behaviour of drilling systems. This model uses a new failure criterion that describes the failure of anisotropic rocks, during the rock cutting process, by introducing the notion of fictitious isotropic material obtained by using a linear anisotropic operator.

## 2 CUTTER-ROCK INTERACTION MODEL

The model presented here relates to the PDC cutter (Polycrystalline Diamond Compact) (Figure 1). The objective of such model is to estimate the forces applied on a single cutter knowing its geometry (back rake angle, side rake angle, diameter, chamfer, …) and the mechanical failure characteristics of the rock.

### *2.1 Isotropic rocks*

In the litterature, the most models utilise shear rock failure criterion such as Coulomb criterion in which the rock is described by its cohesion $C$ and internal angle of friction $\phi$, derived from triaxial compressive tests.

Ecole des Mines de Paris has developed a complete model, detailed in Gerbaud et al. (2006). The model assumes that each cutter of the drilling bit cuts the rock at a significant depth of cut and produces chips with a given geometry. It takes into account build-up edge of crushed materials, chamfer and back cutter force, uses limit analysis and Mohr-Coulomb criterion to calculate the specific energy $R_{eq}$ defined as the ratio of horizontal cutting force over the cutting area (Figure 1). $R_{eq}$ can be written formally as :

$$R_{eq} = R_{eq}(C, \phi, \omega_c, \theta_f)$$

where $\omega_c$ is the PDC back rake angle and $\theta_f$ the friction angle between the PDC and the rock.

For laminated (orthotropic) rocks, the problem is different because the specific energy depends also on the orientation of the formation dip defined by the unit normal $\vec{e}$. As we can see in Figure 2, it is logically easier to cut the rock in configuration (1) than configuration (2).

Since the various cutting tests conducted in laboratory have shown that the utilisation of Mohr-Coulomb criterion can not capture the cutting force variation in laminated rocks, a new single cutter model has been developed based on an appropriate transverse failure criterion.

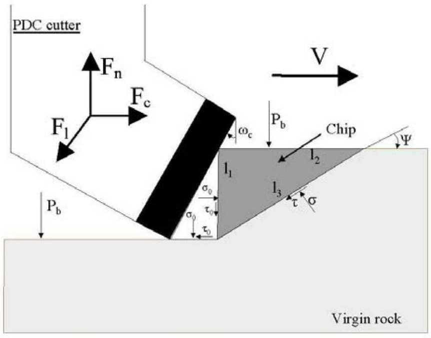

Figure 1 : Cutting forces model.

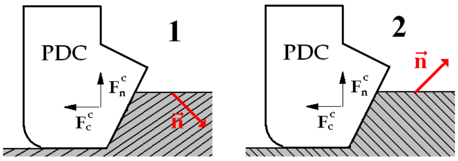

Figure 2 : Cutting configurations in laminated rock.

### *2.2 Proposed transverse failure criterion*

The general form of a failure surface can be expressed by a scalar-valued function $F(\underline{\underline{\sigma}})=0$, which describes the failure envelope in six-dimensional stress space. In order to respect the material frame-indifference, F must necessarily be invariant relative to the material symmetry group.

The material structure can be defined by the symmetric tensor (Boehler & Sawczuk, 1977) :

$$\underline{\underline{e}} = \vec{e}\otimes\vec{e}$$

It can be shown that by adding the structural tensor, $\underline{\underline{e}}$, to the original arguments of $F$ , one can construct a function which is invariant relative to the orthogonal second-order tensors space (Zheng, 1994). Thus, for transversely isotropic material, F can be expressed as:

$$F(\underline{\underline{\sigma}}) = \bar{F}(\underline{\underline{\sigma}})$$

where $\bar{\underline{\underline{\sigma}}} = \underline{\underline{\ell}}(\underline{\underline{\sigma}},\underline{\underline{e}})$, $\bar{F}$ and $\underline{\underline{\ell}}$ are invariant relative to the orthogonal second-order tensors space. Considering this generalization, one can take all the advantages of the well-established theory of the representation of isotropic functions. $\bar{\underline{\underline{\sigma}}}$ can be interpreted as the stress tensor within a fictitious isotropic solid. The real and the fictitious stresses are related by the transformation function $\underline{\underline{\ell}}$. In this work we will use the relationship established by Rouabhi et al. (2007) and which can be expressed in terms of the first and the second invariant of $\bar{\underline{\underline{\sigma}}}$ as:

$$\begin{cases}\bar{p} = p\\ \bar{q} = \left(q^2+\alpha T^2+\beta(p-N)^2\right)^{1/2}\end{cases}$$

where :

- $p$ is the mean or the hydrostatic stress (positive in compression);
- $q$ is the Von Mises equivalent stress which, in triaxial test is reduced to the absolute value of the difference between the axial and the lateral pressures;
- N and T are respectively the intensity of the normal and the shear stress acting across the cut plane normal to the unit vector $\vec{e}$ .

In the transformation above, the material is characterized only by two material constants $\alpha$ and $\beta$. The advantage of using $\bar{F}(\bar{\underline{\underline{\sigma}}})$ instead of $F(\underline{\underline{\sigma}})$ is to use failure surfaces developed for isotropic materials. In order to respect the material symmetry, $\bar{F}$ must only depend on the principal invariants of $\bar{\underline{\underline{\sigma}}}$. In geomechanics, failure of isotropic material is described, in the most case, by the well-known Drucker-Prager and Mohr-coulomb surfaces. In this work, we define the Drucker-Prager failure criterion for the transversely isotropic material.

In the principal fictitious stress space, the Drucker-Prager surface is a cone with a circular deviatoric section centered on the hydrostatic axis:

$$\bar{F}(\bar{\underline{\underline{\sigma}}}) = \bar{F}(\bar{p},\bar{q}) = \bar{q}-\gamma\bar{p}-\lambda = 0$$

where $\gamma$ and $\lambda$ are two material constants.

In order to write the failure surface for the real material, we have to replace in the equation above $\bar{p}$ and $\bar{q}$ by their expressions in terms of p, q, T and N, and thus

$$\begin{aligned}\bar{F}(\bar{p},\bar{q}) &= F(p,q,N,T)\\ &= (q^2+\alpha T^2+\beta(p-N)^2)^{1/2}-\gamma p-\lambda = 0\end{aligned}$$

As a result, we obtain a failure surface with four material parameters $(\alpha,\beta,\gamma,\lambda)$.

In geomechanics the experimental data are obtained in most cases from triaxial tests. Figure 3 illustrates some results of triaxial tests used to identify the mechanical behaviour of Trounemire shale. It shows the variation of the failure compressive strength (Q) with the orientation of lamination for three different confining pressure (P). The experimental results are represented by symbols. Dashed lines correspond to the results given by the four-parameter model. All the curves demonstrate the similar nature of the responses of Tournemire shale under confining pressures, the maximum strength is obtained for vertical oriented angle while the minimum strength is found around 45° dip angle . As shown in the Figure 3, the influence of the confining pressure on the strength characteristics is rather well described.

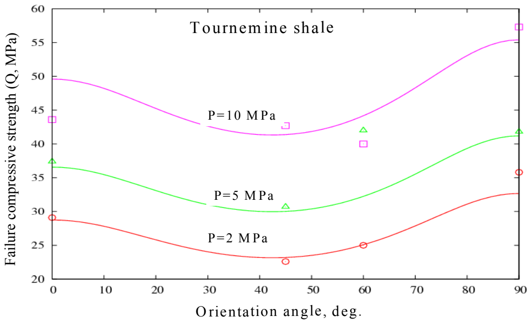

Figure 3: Failure compressive strength variation as a function of anisotropy orientation.

### 2.3 *Application to the Cutter-rock interaction model*

In order to determine the forces applied on the single cutter when cutting a laminated rock (Figure 2), we assume:

i) A fine layer of crushed rock exists between the cutter and the produced chip.

ii) The stress state in the chip is homogeneous and equilibrates the cutter action and the drilling mud pressure $P_b$. It is expressed as :

$$\underline{\underline{\sigma}} = \begin{pmatrix} -\sigma_0 & tg(\theta_f)\sigma_0 & 0 \\ tg(\theta_f)\sigma_0 & -P_b & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

where $\sigma_0$ is the unknown stress applied by the crushed zone to the chip and $tg(\theta_f)$ a friction coefficient.

iii) The chip formation is governed by the transverse failure criterion presented above :

$$F(\underline{\underline{\sigma}}) = F(\underline{\underline{\sigma}}(\sigma_0)) = 0$$

The resolution of the previous equation allows us to calculate $\sigma_0$ as a function of $(\vec{e}, \theta_f, \alpha, \beta, \gamma, \lambda)$.

The rock failure parameters are usually evaluated from classical triaxial compressive tests. However, for a better description of the rock cutting process, we have designed a special circular cutting test, taking into account the 3D variation of dip orientation during the cutter action. This test consists in cutting a circular groove (Figure 4) in an orthotropic rock. During a test on a rock sample at a given dip angle, the variation of the angular position $\theta$, allows the cutter to load the rock in different configurations. Thus, one test is enough to adjust the parameters $(\alpha, \beta, \gamma, \lambda)$. Once these parameters determined they are kept constant for any other dip angles. Figure 5 presents a comparison between the model and the experimental result for 45° dip angle. We can note, in this case of orthotropic rock, that the specific energy is very sensitive to the angular position and the model can describe well this sensitivity.

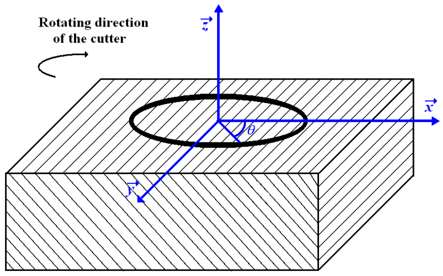

Figure 4: circular cutting test configuration.

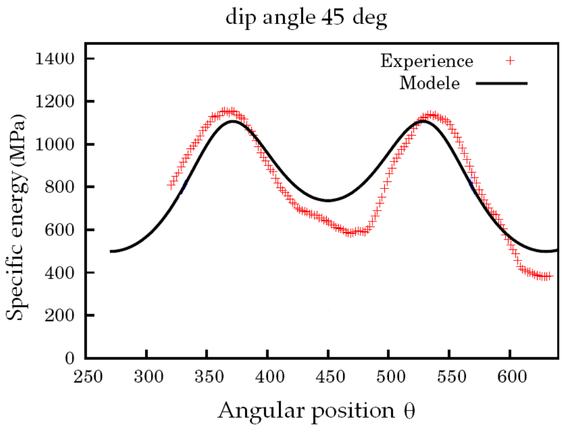

Figure 5: Model-Experiment comparison at 45° dip angle in Tournemire shale.

## 3 DRILLING BIT-ROCK INTERACTION MODEL

The aim of developing a drilling bit-rock interaction model is to describe a relation between the forces applied on a PDC bit (Figure 6) and its resulting displacements. Based on a kinematical approach, the model uses the PDC cutter-rock model to determine the force on each PDC and adds all those forces to obtain the global forces on the bit (WOB, side force, TOB and bit bending moments).

For inter-bedded rocks, during the revolution of the PDC bit, the cutters may be either on the hard rock or on the soft one. The model checks the radial position of each cutter relative to the interface and uses the adequate parameters of the rock. For laminated rock, the model computes the orientation of the formations dip relative to the cutting direction of each cutter before force calculation.

## 4 DIRECTIONAL LABORATORY DRILLING TESTS

The PDC bit-rock model has been validated by various tests on the full scale directional drilling bench of Ecole des Mines de Parois. The drilling bench allows testing drill bit under simulated downhole conditions. Two sets of strain gauges are mounted on the drilling shaft to measure the bending moments (magnitude and direction). The total resulting lateral force value and direction are computed.

### 4.1 *Inter-bedded rocks drilling tests*

These tests are carried out in order to study the effects of the interface angle, and the bit profile when crossing a hard/soft or soft/hard rocks interfaces. The test procedure consists in drilling a sequence of two different rocks with an inclined interface, recording the forces on the bit (side force, WOB, TOB and bit bending moments) and measuring the deviations of the drilled borehole. In this campaign different rocks and bits have been used.

As long as the bit drills only through the soft rock vertically, it does not generate a side force on the shaft, but when it starts to cut the hard rock, the anisotropic side force is created making it deviates. Figure 6 shows plots of the shaft side force and anisotropic force versus the bit position.

The shaft side force increases up to a limit $F_{max}$ and begins to fall as the cutting structure drills more in hard rock than in the soft one. At this moment the shaft side force makes the bit back to the vertical position. For most cases, the bit deviates initially toward the soft rock and then moves to the hard rock.

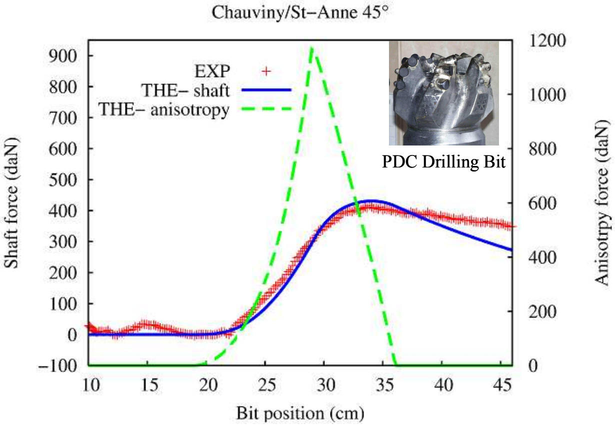

Figure 6: Side force during crossing rocks interface at 45°

The theoretical and experimental results showed that more deviations are occurred when the interface between the rocks is close to the vertical. In addition, the results indicate that the deviation decreases when the stabilisation gauge of the bit increases.

### 4.2 *Laminated rocks drilling tests*

The tests in laminated rocks consist in drilling a vertical hole through a cylindrical shale sample with a diameter 20 cm and length 45 cm. The dip angle is changed from 5° to 85°. Figure 7 presents the variation of the WOB and side force measured on the bit when drilling a shale sample with a dip angle of 30°. These results prove clearly the existence of a side force which is mainly due to the rock anisotropic behaviour. The sample length is probably too short to obtain stabilization of the side force. Figure 8 shows the side force evolution as a function of the dip angle. The tests for which the side force stabilization does not occurred are marked with arrows. At 0° and 90° dip angle the side force is low. As the dip angle is around 50°, the side force is maximal and reaches 16% of WOB. For most tests, the side force direction varies from -20° to 45° around the down to up direction.

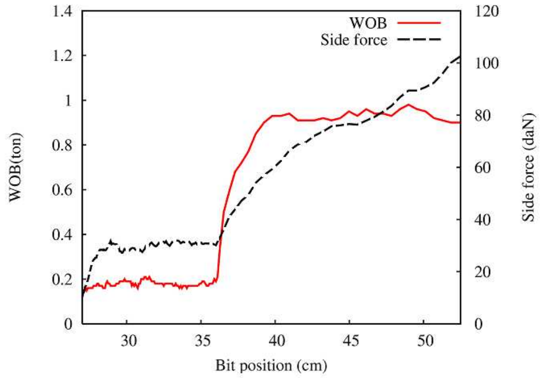

Figure 7 : WOB and side force in 30° dip angle shale sample.

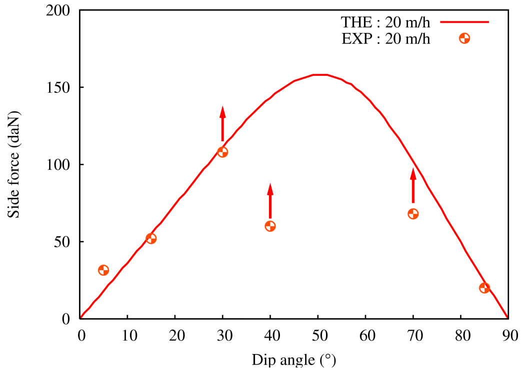

Figure 8 : Side force in shale vs. dip angle shale.

## 5 TRAJECTORY PREDICTION MODEL

The parameters that affect directional system behaviour can be classified in two groups related to:

- Bit-rock interaction: bit steerability, walk angle, rock anisotropy (Boualleg, 2006).
- Drill string mechanics: drill collars, stabilizers, bent subs, downhole motors, etc…

A new 3D code, based on direct integration of the stiff strings behaviour and equilibrium equations without using the finite element method, has been developed at Ecole des Mines de Paris (Menand et al., 2005). This code, enabling to simulate any BHA or drillstring (Torque&Drag, buckling, directional, …), is coupled to the 3D rock-bit model. The calculations are made stepwise with an algorithm in order to predict drilling trajectory feet by feet. This algorithm has been validated on data from actual wells.

### 5.1 *Deviation in inter-bedded rocks*

In order to analyse the effect of drilling an inter-bedded rocks on the well trajectory, we simulate the case of a BHA#1 (Figure 9) coupled with a bit having a given steerability and walk angle. Initially this system drills a soft rock and enters suddenly another one 5 times harder, at an 60° interface angle.. Figure 9 presents the variation of the inclination as a function of the measured depth with various WOB when crossing an inter-bedded rocks at 75°. We note that in the soft rock the inclination is constant and a sudden deviation (dogleg) appears when crossing the interface. The well inclination increases of 3.5° in less than 0.4 m. Three meters following this first deviation, a second deviation occurs even if the bit drills on homogeneous rock. Indeed, the sliding of the first stabilizer through the first dogleg causes a second local dogleg. These undulations are repeated each time the first stabilizer crosses a dogleg. The bit behaviour, looking like a harmonic movement, can be amplified or attenuated, depending on BHA, bit and operation parameters. Figure 9 shows also that increasing WOB may reduces considerably the amplification of trajectory undulations. Others simulations have demonstrated that the position of the first stabilizer has a strong correlation with the period of oscillations as observed in the field.

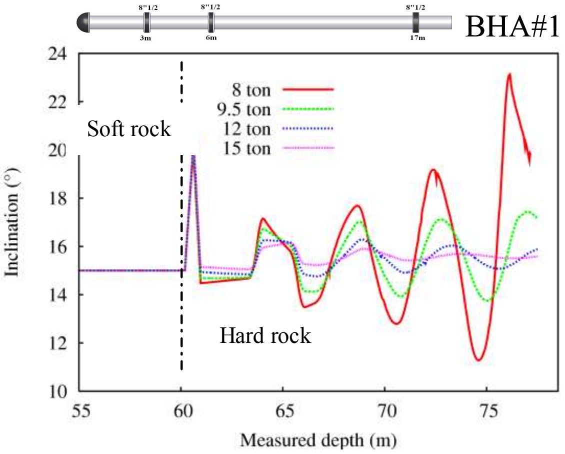

Figure 9: Effect of WOB on the inclination of drilled hole when crossing inter-bedded rocks at 75° interface angle.

### 5.2 *Deviation in laminated rocks*

The difference between inter-bedded and laminated rocks effect on trajectory behaviour is explained by the origin of the side force. For an inter-bedded rock, the side force is created locally and for a laminated rock it is continuously created as the bit remains in the rock. For this reason, drilling laminated rock should have a more significant large scale effect. Figure 10 presents the evolution of the hole inclination with the drilled depth for two different BHA, a dropping BHA#2 and a building BHA#3.

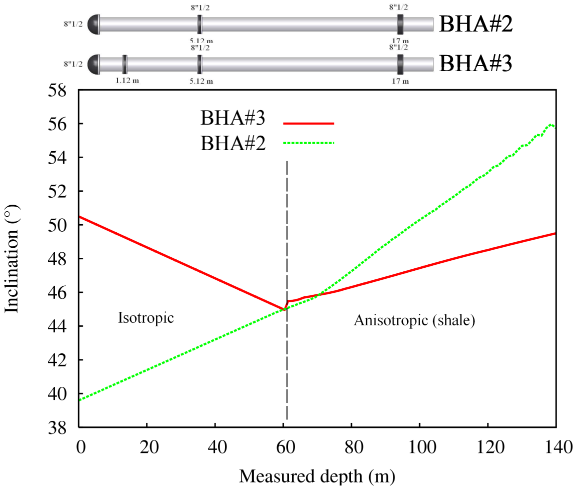

Figure 10: Effect of anisotropy on trajectory build/drop rate.

The two BHAs drill in an isotropic formation and then encounter into a shale formation with dip angle 45°, at 62 m measured depth. We notice that the slope of the curve changes from 2.7°/30 m to 4.3°/30 m for BHA #3 and from -2.75°/30 m to 1.64°/30 m for BHA#2. These findings show that rock anisotropy has changed completely the behaviour of the directional systems leading to hazardous trajectory control.

## 6 CONCLUSION AND FIELD RECOMMENDATIONS

An interaction bit-rock interaction model based on a PDC single cutter model has been developed to calculate the side force on PDC bit drilling an anisotropic formations (inter-bedded or laminated rocks). The models has been validated and calibrated on a full-scale drilling benches. Coupling the 3D bit-rock model with BHA mechanical behaviour model allows predicting trajectories through isotropic, inter-bedded and laminated rock formations.

Simulations have shown that when the nature of the drilled formations is known, it is possible to take some actions to minimise the consequence of the formation anisotropy:

- WOB: to minimise the risk of amplification of trajectory oscillations in inter-bedded rocks, we recommend increasing WOB. However for laminated rocks it is recommended to decrease WOB in order to reduce well deviations.
- Bit design: as deviations are caused by the side force, decreasing side cutting ability of drilling bit may minimise deviation in anisotropic formations.
- The risk of amplification of trajectory oscillations is controlled mainly by the nearest stabilizer to the bit. Increasing the distance between the bit and the first stabilizer may decrease this risk.
- In laminated rocks, stiff BHA with a near bit stabilizer may resist more to the lateral deviations.

## 7 REFERENCES

Boehler JP, Sawczuk A., 1977. On Yielding of oriented solids. Acta Mechanica . 27:185-204

Brown E.T., Geen S.J., Sinha K.P. 1981. The influence of rock anisotropy on hole deviation in rotary drilling. Int, J Rock Mech. Min. Sci and Geoch. pp 387-401.

Boualleg R., 2006. Etude du comportement des systemes de forage en formations geologique anisotropes, PhD thesis of Ecole des Mines de Paris.

Gerbaud L., Menand S., Sellami H., 2006. All comes from the cutter rock interaction. SPE paper N°98988. IADC/SPE Drilling Conference, Miami, Florida.

Menand S., Sellami H., Tijani M., Stab O., Dupuis D., Simon C., 2005. Advancement in 3D drillstring mechanics: from the bit to the Topdrive. paper SPE 98965. IADC/SPE Drilling Conference, Miami, Florida.

Reich M., Oesterberg M., Montes H., Treviranus J., 2003. Straight down to success. Paper SPE 84451. SPE annual Technical Conference, Denver, Colorado.

Rouabhi A, Tijani M, Rejeb A, 2007. Triaxial behaviour of transversely isotropic materials – Application to sedimentary rocks. Accepted for publication in the International Journal for Numerical and Analytical Methods in Geomechanics

Simon C., 1996. Modelisation of PDC bit directional behaviour in anisotropic formation. PhD thesis of Ecole des Mines de Paris

Zheng QS., 1994. Theory of representations for tensor functions – A unified invariant approach to constitutive equations. Applied Mechanics Review 1994; 47:545-587.