Mechanical Earth Model and Integrated Geomechanics Approach as New Frontier For Petroleum Industry*

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Abstract: Geomechanics (the study of rock deformation and failure) is gaining wide recognition in the petroleum industry worldwide. Applying geomechanics modeling allow achieving significant financial benefits to oilfield operations ranging from exploration and field development to reservoir management. Central to creating value through application of geomechanics is a closed loop process that links a mechanical earth model (MEM) with fit-for-purpose-engineering software, multi-disciplinary teamwork and knowledge management1,2)

This publication provides an introduction to a MEM based integrated geomechanics process and demonstrates how operations throughout the life cycle of field benefit from the closed loop geomechanics approach. A case study introduced in this paper illustrates how MEM integrated with iterative Real Time approach helps to overcome challenges and reduce financial risk during drilling operations and field development overall.

Key words: geomechanics, mechanical earth model, MEM

1. Introduction

Over one billion dollars a year oil and gas industry spends for non-productive time and to cover the cost of the extra strings of casing, the tools lost in hole, sidetracks and other remedial operations. Significant amount of this is taken by the time spent managing kicks, mud losses, excessive circulations, stuck pipe and other related events. Some events occur due to lack of planning, which makes it unavoidable. Some events occur due to lack of execution that makes the events impossible to prevent and difficult to control. This clearly illustrates that there is a great financial risk associated with the drilling operations and field development where there is very little or no geomechanics information available.

Confidently knowing safe mud weight window allow for better planning and well construction. It addresses the major concern of drillers - pore pressure. However, pore pressure is only a subset of the overall problem of wellbore stability, as even normally pressured formations do not imply trouble free drilling. In many cases there is a problem of keeping the wellbore stable, at which point the mud weight is constrained by the minimum stable pressure and fracture gradients. This minimizes the permissible safe mud weight window and unawareness could cause overpulls, hole-cleaning problems, pack offs, lost in hole equipment and loss of circulation. This could lead to costly sidetracks or the loss of the wellbore. To achieve safer operations and enable successful
drilling of technically and economically challenging wells an integrated geomechanics approach has been designed and proven in numerous cases.

Building a mechanical earth model, that could be used for planning and design and revising it in real time, to deliver the right information to the right people at the right time has been the key to successfully drill complex wells on and below the AFE.

This paper provides some information on the integrated geomechanics process that is used to solve oilfield problems, concentrating on the drilling aspect, as well as introduces one of the case studies based on the operations in Gulf of Mexico. The case study presented is based on the paper and presentation written for AADE Conference held in April 2003 Houston, USA by Smirnov, N., Lam, R., Rau III, W, called "Process of integrating Geomechanics with well design and drilling operation".

2. Geomechanics Model and Its Application

The mechanical earth model is a numerical representation of the rock mechanical properties and state of stress (including pore pressure) for a specific stratigraphic section in a field or basin.

The general ten steps of building the mechanical earth model are shown on Fig. 1, where Data Audit should be specifically mentioned. The two main goals of the data audit is to understand the geomechanical issues that may cause financial risk and to understand what data is and is not available and how it could be used to mitigate this risk3).

The model utilizes multi-disciplinary data from geology and geological structure and seismic information, wireline logs, borehole images, pressure data, core tests to drilling measurements and drilling mechanics information.

After rigorous calibration of 1D and 2D Mechanical Earth Models (MEMs) that capture the 3D stress state, strengths, elastic and mechanical properties of the rock and deformation mechanism of the overburden and reservoir formations a 3D Mechanical earth model is built.

Calibrated 3D MEM is widely used in the oilfield; some of the applications are listed below. Pore pressure and fracture gradient prediction as well as full wellbore stability model is used to identify safe and stable mud weight window for well design, planning and drilling. Knowledge of pore pressure, stresses and rock properties together with the other parameters allow to predict onset of sanding production, establish the best possible direction and placement for perforations, avoiding damaged while drilling zones. It allows for a significant improvement to the fracture stimulation design, as well as completion design itself. As the reservoir is produced geomechanics models can predict reservoir compaction and start dealing with the problems related to subsidence that may cause casing shear, collapse and loss of a producing well. Having comprehensive geomechanics model helps to address problems associated with water and gas injection, reservoir behavior, fault stability and induced seismicity, as well as underground storage and disposal for reservoir management4,5).

The complexity and predictability of the MEM evolves with introduction of new data, as presented on the Fig. 2. Whenever no well information is available all geomechanics information comes from basin and geological models, seismic data constrained by rock physics and possibly geomechanics analogs. At that stage MEM can be used for planning of an exploration wells and may include a 3D struc-
Fig. 2 MEM development through the field life tural framework model, a shallow water hazards analysis and a prediction of the pore pressure and fracture pressure profiles, which can be extracted from the 3D model along the planned trajectory. The basic MEM is adequate for running drilling simulators to estimate probabilistic well costs and relative operational risk.

Once the first well is drilled, the 3D model can be revised and improved with a fully calibrated MEM along the trajectory to TD. By incorporating data and knowledge of the first several wells, the model can grow to a calibrated 3D MEM. The scenario continues as more data are acquired improving the predictive power of 3D MEM and thus allowing for better well planning, field development completion and reservoir management.

3. Real-Time Implementation

Whatever the best representation of the earth properties and conditions you can achieve, the problem still remains along the actual trajectory. The best available information for the planned well comes from modeling, with its uncertainties and assumptions. The real environment starts to become known only as the drilling bit penetrates the formations and observation and measurements are available. In spite of how detailed and how expertly engineered it is, a predrill model is obsolete almost as soon as the new information comes to light. This uncertainty has to be dealt with and managed in real time.

To gain the full value of the geomechanics and to deal with the uncertainty, mechanical earth model has been tightly integrated in a closed loop feedback system, presented on Fig. 3. This is a process that allows for updating geomechanics model in real time based on the information, measurements and observation from drilling, monitor and ensure safe operations, mitigate the risk, and enables capture and knowledge transfer.

4. Geomechanics Consideration within the Drilling Program

A 3D Mechanical Earth Model once built can be used by the drilling engineers for planning and ell design. Based on geomechanics knowledge the most stable trajectory direction can be planned for; also, depending on the well path, profiles like pore pressure and fracture gradients are vary, this allows to design the safest and easier to drill trajectory. On the Fig. 4 there is an example of extracting a pore pressure and velocity profiles from 3D MEM along the arbitrary trajectory.

Having calibrated predrill profiles of pore pressure and fracture gradient profiles is the bases for mud program and casing seat selection and design, it also impacts BHA and drill string selection and therefore torque and drag with swab and surge need to be considered. Some of the drilling practices depend on the type of possible instabilities that may be experienced while drilling, for example in the stressed formation with breakout type shear failure,
backreaming should be avoided. Knowledge of unstable depth intervals, and failure severity helps to identify proper drilling practices and procedures. Understanding causes of the events like instability provides additional information to analyze drilling events, which allow altering the drilling and completion operations in real time to achieve desirable results.

5. Case Study

The Petronius field is located in the Gulf of Mexico at the frontier between the shelf and deep waters. At the water depth of 1,750 ft it's been one of the deepest fixed drilling structures in the world. One vertical and several deviated wells have been drilled in different directions from the platform. As the reach extended further away from the platform and the inclination increased the operations started suffering from tight hole, pack offs, lost circulation and tools lost-in-hole. To overcome these problem and continue the development the operator, ChevronTexaco, began utilizing geomechanics modeling and real time process. This allowed for better design and therefore more aggressive well profiles.

This solution provides pre-drill modeling, real-time model updating and implementation of the resultant changes at the rig site to lower and manage the risks and reduce non-productive time. As a result of applying the process and open collaboration series of extended reach wells have been successfully drilled with significant time (of up to 30%) and money savings for the operator.

This case study is related to the sixth ERD and its geological sidetrack in the field A-21 and A-21 ST1.

5.1 Well Design

Petronius ERD wells have common design:
- Preset 20 in. conductor pipe
- 17-1/2 in. hole with 13-3/8 in. casing through the build up section
- 12-1/4 in. hole in the tangent section with 9-5/8 in. casing, where inclination varies around of 80 degrees and
- 8-1/2 in. hole with 7 in. liner in the reservoir section

Using geomechanics knowledge for planning and applying it in real time saved from additional casing strings and kept the design un-
changed. However some innovations were used such as drilling 8-1/2 in. by 9–1/4 in. hole using bi-centered bit on the rotary steerable.

5.2 Objectives and Challenges
The main objectives, besides reaching the penetrating the reservoir were to:

- Place 9–5/8 in. casing past the unstable zone before drilling into lower fracture gradient formations with higher mud weight
- Avoid high over pulls, stuck pipes, lost-in-hole, loss circulations
- Monitor ECD and ESD within the limitations established during the predrill preparations and, constrain in real time
- Monitor hole conditions, and drill within rig limitations

The water depth varies around the platform from 700ft to 3,400ft depending on the azimuth. This created one of the modeling challenges, as the overburden stress varies along the trajectory depending on the water depth. On the way to the reservoir dipping formations and low-pressure sands had to be drilled. Due to the extended reach some unknown formations had to be penetrated.

5.3 Modeling
A full 3D Mechanical Earth Model (MEM) 4) was built using 3D seismic, logs and tests information and incorporated drilling experience from all the wells previously drilled in the area.

Fig. 5 shows in blue a comparison of the overburden estimated with (red) and without (blue) taking into account water depth variation.

New safe margins had to be established due to the narrow stable mud weight window. The acceptable magnitude of the borehole wall failure that could be handled by the rig hydraulics was estimated. The emphasis was made on real-time ESD/ECD to be greater than failure initiation pressure (Fig. 6).

Drilling mechanics response was modeled and optimized upon the stability prediction.

Torque and Drag analyses were conducted and theoretical profiles calibrated with the real time of pick up and slack off weights data (Fig 7).

Limitations of the most essential rig equipment were considered in the modeling for preventing and eliminating potential failure.

For this particular well it was identified that instability will be met shallower due to trajectory and structural features. This drove the decision for the placement of the 13–3/8in. casing, as well as that A–21 original hole could be completed with 12–1/4in. size hole. In case the reservoirs cannot be found the sidetrack option was planned with 8–1/2in. by 9–1/4in. hole. The drill out parameters and mud weight were identified.

5.4 Real Time Updating
As certain degree of the hole instability was allowed to make the wells drillable to successfully manage drilling in such conditions close monitoring was applied.

The following log measurements were used for real time model update: gamma ray, resistivity, sonic, density and porosity from the neutron tool.

ECD management and real time model update with continues monitoring helped to overcome the main challenge of keeping borehole from both collapsing and fracturing. Even though some fractures were induced, they were successfully identified and treated.

Understanding the possible processes occurring in the well, permitted real time interpretation of the log and drilling parameters response. Pick up, slack off and rotating weights of the drill string calibrated and compared with the actual measurements while drilling and on every trip (Fig 7). On this figure the dashed curves are the theoretical pick up/slack off weights. Solid lines are the actual measured weights of the drill string with the depth.

The ability of comparing modeled parameters with the real time observed ones provided an overall understanding of the condition and the processes occurring in the well. The correct interpretation of this information together with ECD and drilling parameters provided ac-
5.5 Results and Conclusions

The sixth ERD well and its geological sidetrack were successfully drilled applying Real Time WBS Management Process and integrating across various disciplines. The well bore was drilled safer and more efficient.

There were no stuck pipe incidences, lost-in-hole or costly sidetracks. Losses and instabilities were successfully managed. All the targets were reached and all of the casings went to the planned TD.

The drilling of the original hole was on the AFE plan (excluding the waiting on weather and time spent on installing equipment). The sidetrack was drilled 16 days under AFE.

For a complete description of this project see references6,7).

6. Conclusion

To successfully manage drilling and avoid taking financial risk, the mechanical earth model should be used in both planning and execution phases. To gain all the benefits of the MEM, the uncertainty of the model have to be resolved in real time propagating model confidence ahead of the bit (for drilling). The pre-drill geomechanics model once integrated in a closed loop feedback system can be continuously updated in real time with the new information from the tools and observation. Correct implementation of the process over the field life cycle brings significant financial saving to the operations and allows to improve safety and performance.

Nomenclature

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
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<tr>
<td>AFE</td>
<td>Authorization For Expenditure</td>
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<td>BHA</td>
<td>Bottomhole assembly</td>
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<td>ECD</td>
<td>equivalent circulation density</td>
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<td>ESD</td>
<td>equivalent static density</td>
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<td>ERD</td>
<td>Extended reach drilling</td>
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<td>MEM</td>
<td>Mechanical Earth Model</td>
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<td>TD</td>
<td>total depth</td>
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<td>WBS</td>
<td>Well Bore Stability</td>
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SI Metric Conversion Factors

<table>
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<tr>
<th>Unit Conversion</th>
<th>Conversion Factor</th>
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<tr>
<td>ft</td>
<td>3.048 × 10^-1 m</td>
</tr>
<tr>
<td>inch</td>
<td>2.54 × 10^-2 m</td>
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<tr>
<td>lbm/gal</td>
<td>1198264 × 10^-2 kg/m^3</td>
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*Conversion factors are exact.

References


要　旨
石油産業における新開地としてのメカニカルアースモデルと統合的ジオメカニクスの取り組み方について
ニコライ スミルノフ
ジオメカニクス（岩石の変形および破壊に関する研究）は各国の石油業界において広がり認識を得ており、ジオメカニクスモデリングは油田作業において開発から貯留層管理に至るまで、多大な経済利益をもたらしている。ジオメカニクスの応用による価値の創出において最も重要な点は、メカニカルアースモデル（MEM）を目的にしたソフトウェアや複数の専門分野でのチームワークならびに知識管理にリンクさせるフィードバック手法にある。

MEM とは、フィールドにおける特定の層位部分の岩石の機械的性質や応力状態を数値的に表したものである。MEM は、間隙水圧予測、掘削時の構成の安定性、出砂の始まりの予測、パフォーマーションおよび仕上げ用水圧破砕デザインなど多数の油田作業への応用のみならず、貯留層圧縮および沈下の予測、水およびガス注入、貯留層の性質、断層の安定性および誘発地震、貯留層管理における地下貯藏/廃棄などの仕上げデザインへの運用が可能である。

MEM の複雑さと予測可能性は、新たなデータを導入することによって進化させることができる。最初の試掘井の掘削が開始される前には、すべてのジオメカニクスの情報は、岩石物理学に基づいたモデルや地震データ、あるいは企業の知識共有システムにより取得した地理学的類似物などより取得される。掘削開始前の MEM には、3D での構造的枠組みモデル、ジャローチャートの危険分析および間隙水圧や地層破壊圧の傾向予測などを含むが、これらの基礎的な MEM は、坑井費用の概算あるいは作業時のリスク予測のための掘削シミュレーションを行うのには十分である。しかし、いったん最初の坑井の掘削を開始すれば、MEM の適応範囲を修正あるいは拡張し、また TD への坑跡に沿った完全にキャリプレートされた MEM を得ることができる。さらに、最初の 3 ないし 4 本の掘削井のデータおよび情報を取り込んだ後、そのモデルをキャリプレートされた 3D MEM に発展させることも可能である。データを取りっていくことにしたがって、3D MEM の予測能力がさらに向上し、これによってよりよい坑井計画と貯留層管理を実現することができる。以上の過程で核となる 4 大要素は、データチェック、MEM、開ループシステムによるフィードバック手法、そして油田のライフサイクルにわたってこれらの工程の実行をサポートするソフトウェアである。

本稿では、MEM の基礎を説明し、ジオメカニクスの油田作業への応用を実際のメキシコ湾での使用例などを含めて解説する。