A Proposal to Develop an Improved Methodology for Wellbore Stability Prediction

Knowledge Systems, Inc.

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1. Executive Summary

Maintaining wellbore stability is a key factor in improving safety and drilling efficiency while minimizing problem costs associated with well construction and production operations. Despite the need to understand the conditions which create instabilities, there is no industry consensus regarding which stability analysis methodologies are most applicable under varying geologic conditions.

Given the success of prior collaborative efforts, a joint industry project is proposed to identify and develop best practices for practical wellbore stability analysis, including a comprehensive survey of existing methods, an assessment of relative priority of data types required, and the development of new process and techniques through the study of approximately 250 wellbores from five regions around the world. The resulting database and methodologies will be designed for ready implementation by drilling engineers.

The proposal envisions approximately 15 participating E&P firms and contractors and a total project budget of $1,483,500, or $98,900 per participant. Project duration will be approximately 18 months. Participants are expected to be actively engaged in the drilling management or providing drilling services wells in the areas of interest.

Analysis will be conducted by an experienced multi-disciplinary team of geomechanics engineers, drilling engineers, geologists, geophysicists and petrophysicists. Alternative stability modeling methodologies will be reviewed, documented and assessed to identify current best practices. We propose five geologic areas to be examined in detail using the most promising approaches. Stability models will be developed based on the analysis of approximately 50 wellbores per area. Established software systems will be used and a database of digital well data and results will be built and maintained. The proposed data will be procured from publicly available sources and delivered to the participants upon project completion.

The main objective is to identify which currently used methodologies are most effective predicting actual wellbore stability conditions and to establish and document guidelines for their use. A secondary objective is to improve existing methodologies. New wellbore stability analysis models and improved tools for defining and constraining rock strength estimates will also be developed.

The project team’s progress will be guided by a technical advisory committee comprised of industry experts from all participating companies. Knowledge Systems will provide or obtain the necessary software and technical expertise to conduct the research, data collection, analysis and documentation under the provisions detailed in the proposal.

Implementation of the methodology will be accomplished by a combination of technical forums, training courses, reference manuals, an electronic or “smart” manual and an internet web page for keeping the methodology updated.
2. Introduction
Designing a stable wellbore has long been a difficult task for drilling engineers. Responsibility for this important element of well planning varies from company to company and case to case, sometimes involving the drilling engineer, sometimes the geologist, sometimes the geophysicist, and sometimes the petrophysicists. In all cases, the drilling engineer is the person that must have this prediction to make an efficient well plan in terms of casing design, mud weights, mud chemistry, drilling time and safety.

There are several failure models widely used to predict wellbore stability; but there is a diverse range of experience and opinion as to which model is more accurate, and which more applicable under what conditions.

Collaboration is needed to identify and develop best practices for practical wellbore stability analysis. These guidelines should also assess the relative priority of data types and minimum data requirements to perform effective modeling.

3. Background
This project follows on a series of successful joint industry projects focused on predicting earth pressure and in-situ stress and wellbore stresses. Knowledge Systems has been involved in computer assisted pore-pressure and in-situ stress analysis and prediction since 1989, when it began the DEA 59 project that resulted in the development of the DrillWorks Expert software.

Knowledge Systems built on this pioneering work when it initiated the DEA 119 project (completed in 2003) to improve the methodologies used in deepwater pore pressure and fracture gradient prediction. Sub-salt pore pressure prediction is the focus of a current joint-industry project examining several salt mini-basins using 3D geologic Earth modeling.

In the course of this experience and global service work, Knowledge Systems has come to believe that significant improvements in wellbore stability prediction may be achieved through the identification and development of best practices and methodologies.

4. Project Overview
The objective of the project is the identification and development of best practices for practical wellbore stability analysis. The resulting methodologies should be readily applicable by drilling engineers.
There are five essential ingredients that form the basis for this proposed project:

1. A detailed wellbore stability analysis of a significant number of wells (~50 per geographic area) using all available data to include seismic, wireline, drilling and pressure test data such as MDT’s, mini-frac’s and LOT’s.

2. A multi-disciplinary team that includes engineering and geoscience specialists to study the results of these analyses and formulate the improved methodology.

3. The improved methodologies will be blind-tested rigorously and completely documented to validate the performance improvements.

4. The results of all the analyses will be aggregated, sorted and distilled into best practices for practical wellbore stability analysis.

5. The best practices will be delivered via workshops to ensure operations personnel receive maximum benefit from the study and improved methodologies.

It is anticipated that this improved methodology will include some combination of possible new wellbore stability analysis models and/or guidelines for applying existing ones. New tools for defining and constraining rock strength may include temperature effects, a streamlined workflow, or the use of stochastic modeling to constrain highly unknown parameters.

Implementation of the methodology will be accomplished by a combination of technical forums, training courses, reference manuals, an electronic or “smart” manual and an internet web page for keeping the methodology updated.

5. Business Impact

Loss of wellbore stability is the major source of non-productive time while drilling, causing an estimated $8 billion in world-wide losses each year. A clear goal of this project is to identify practical methods that will reduce or eliminate the incidence of unstable wellbores at a fraction of the cost of remediation.

Specifically, this project is intended to increase the effectiveness of drilling engineers in planning for wellbore stability such that the business of the project participants will be improved in the following ways:

- Reduced well construction time and cost
  - Reduced casing related costs
  - Reduced mud costs
  - Reduced dependence on contingency casing designs
- Improve quality of formation evaluation data
- Maintain hole integrity for maximum production
6. Project Sponsor

Knowledge Systems has received confirmation that Marathon Oil Company will provide operator sponsorship for this project. Contact:

John Jones  
Senior Drilling Engineer  
5555 San Felipe Road  
Houston, TX 77056-2725  
USA  
(713) 296-3331  
jfjones@marathonoil.com

7. Scope of Work Outline

The proposed scope of work, detailed in Section 16 below, falls into five major areas:

Research of Current Practices  
We will conduct a thorough review of industry wellbore stability analysis practices, then use the results to select the most promising modeling methods. From available sources, gather the necessary data to test the selected models on a representative sampling of wells.

Data Gathering, Quality Control and Validation  
An assessment will be made to determine the relative priority of data types. Based on the assessment, data will be acquired from available resources and organized within a project database.

Determination of in-situ stress and rock strength  
Assumptions regarding in-situ stress and rock strength parameters are key factors in developing and validating wellbore stability models. A best practice will be developed and validated against available rock strength data from core samples, and used to provide consistent inputs to the wellbore stability models.

Wellbore Stability Analysis  
For each of the selected wellbore stability modeling methods, an analytical wellbore stability prediction will be generated for the selected wells, using the information available pre-drill. Similarly, we will analyze how these predictions could have been modified using information available while drilling.

Separately, a definitive wellbore stability diagnosis will be prepared for each well using the best practices previously identified. The analyses will be correlated to known wellbore instability indicators like deformation, cavings and pack-offs.

Under certain geomechanical conditions analytical methods may not produce reliable results. Numerical methods for modeling wellbore failure mechanisms, like finite element analysis, will be considered as an alternative, provided that such methods are
practical and efficient.

These predictions will be rigorously compared to the actual well diagnoses to determine the best practices for wellbore stability estimation both pre-drill and while drilling.

**Documentation and Communication of Findings**

Project findings will be documented and distributed among participants using appropriate methods, including manuals, expert systems, workshops and training courses.

The final scope of work will be agreed by the project participants.

A schematic of the proposed project workflow is provided below:

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**Figure 1**—Overview of project work scope. Key milestones are shown in red.

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### 8. Project Deliverables

This project will produce the following deliverables to the participants:

1. Monthly project status reports and more detailed interim project progress reports every six months during the project.

2. Based on a study of the analysis results from this project, an improved methodology will be determined for the prognosis of wellbore stability. This methodology is anticipated to be some combination of methods, models, data and procedures that result in an improved prognosis. It may include new models that better fit the analysis results, recommendations for different approaches for
generating velocity data from surface seismic data, and/or recommended well planning procedures.

3. Any new models, algorithms and/or methods for wellbore stability analysis that are developed as a result of this project will be distributed to each participant in digital programmatic form such that they can be directly used in DrillWorks Expert as a User Defined Method or User Defined Program, or, alternatively they can be built into other software by the participant. Each participant will be able to distribute unlimited copies of such new methods within the participant’s company.

4. The methodology will be documented and described in a Wellbore Stability Prognosis Manual. It is anticipated that the manual will be in the range of 100 to 200 pages. Each participant will receive five copies of the manual. Additional copies will be available at cost.

5. The methodology will also be provided in electronic manual form, using a rule-based expert system structure that runs under Windows. Each participant will receive a corporate license to the electronic manual that allows unlimited copies within participant’s corporation.

6. A Wellbore Stability School specifically designed for drilling engineers will be held in each of the project’s geographic areas (five proposed). The course will be 3 days in length and cover the practical aspects of wellbore stability modeling and the associated best practices.

7. The data and analysis results will be maintained in digital form in a relational database such that it will be available for future research and study to include testing new models and methods.

8. A Wellbore Stability website will be created and maintained that contains project results, available data and updated information. This website will require password access and each project participant will be provided with a password that will be updated periodically. It will also include an FTP site that will permit downloading of data in digital form as the owners of the data provide permission for disclosure.

9. **Group Participation**

   Active participation and involvement by project participants is important to the overall success of the project and also to the project benefits realized by each participant. Participant input is needed on 1) selecting specific study areas 2) obtaining data, 3) interviewing persons about current methods and practice, and 4) critiquing the project as it is carried out.
10. Technical Advisory Committee

A Technical Advisory Committee consisting of two representatives from each participating company will oversee the project. Committee meetings will be held at periodic intervals, at which time the committee will review work accomplished and future plans.

11. Technical Panels

The following technical panels will be established for this project:

1. In-situ Stress and Pore Pressure Estimation Methodology
2. Rock Strength Correlation
3. Wellbore Stability Modeling

The purpose of these panels is to provide 1) technical guidance, 2) technical liaison, and 3) forums for technical exchange.

12. Project Reporting and Forums

Participants will receive a project status report following each month during the course of the project and a more detailed project progress report at the end of each six-month period during the project.

A Wellbore Stability School specifically designed for drilling engineers will be held in each of the project’s geographic areas (five proposed). The course will be 3 days in length and cover the practical aspects of wellbore stability modeling and the associated best practices.

13. Initial Project Budget

The initial budget for this 18 month project is as follows:

<table>
<thead>
<tr>
<th>Description</th>
<th>Amount</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Labor</td>
<td>$1,071,900</td>
<td>72.3%</td>
</tr>
<tr>
<td>Software</td>
<td>$220,500</td>
<td>14.9%</td>
</tr>
<tr>
<td>Hardware</td>
<td>$29,400</td>
<td>2.0%</td>
</tr>
<tr>
<td>Travel</td>
<td>$147,000</td>
<td>9.9%</td>
</tr>
<tr>
<td>Production Costs &amp; Incidentals</td>
<td>$14,700</td>
<td>1.0%</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>$1,483,500</strong></td>
<td></td>
</tr>
</tbody>
</table>

A minimum of 10 participants will be required to initiate the project. If the total number of participants is more than 10 and less than 15 six months after the kick-off, the project scope will be reduced with the guidance of the project council of project.
participant representatives.

The Drillworks Expert software system will be used for the project and all project results will be in the Pressworks database. At any time during the course of the project, participants will have the option to purchase one single user license of the office version of Drillworks Expert for Windows at a 15% discount from the then current license fee.

14. Project Duration
The anticipated project duration is 18 months, as detailed in the following chart.

<table>
<thead>
<tr>
<th>Research of Current Practice</th>
<th>2007</th>
<th>2008</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Q1</td>
<td>Q2</td>
</tr>
<tr>
<td>Data Gathering and Quality Control</td>
<td></td>
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<tr>
<td>Determination of In Situ Rock Stress and Strength</td>
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<td></td>
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<tr>
<td>Wellbore Stability Analyses</td>
<td></td>
<td></td>
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<tr>
<td>Documentation and Communication of Results</td>
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Figure 2–Proposed project timeline.

15. Data Sources
It is anticipated that most of the data used in this project will be acquired from available sources. If participants determine that the analysis needs to be supplemented with proprietary data, such data will be maintained in a secure facility on a confidential basis and be used for analysis, study and conclusions pertinent only to this project. Detailed analysis results will only be provided to the owners of the data for a particular well, and will not be disclosed to other participants without written permission by the owner. Only summarized analysis results that will be generalized and normalized will be presented in reports that are provided to all participants. The project contract will include strong protective non-disclosure provisions and all employees and consultants that work on the project will sign individual non-disclosure agreements. Knowledge Systems has routinely been entrusted with proprietary data from major operators in the normal course of its geopressure analysis business over the past nine years.
16. Detailed Scope of Work

The detailed scope of work for this project is as follows:

Research of Current Practices
1. Review and document current industry practice for wellbore stability prediction in vertical and inclined wells, including conventional and deepwater applications. Survey, document and classify various wellbore stability models and methods from literature. Select a group of models and methods to apply in wellbore stability computations for the project wells.

Data Gathering, Quality Control and Validation
2. Collect and validate well data from available sources for modeling tests in areas to be determined by project participants (current targets: North Sea, Australia, GoM Shelf, GoM deepwater, and Western Canada).

Determination of in-situ stress and rock strength
4. Obtain rock strength parameters either from core tests or correlations; analyze rock strength and petrophysical data to obtain new correlations for each study area.
5. Analyze rock strengths, rock stresses, pore pressure and fracture pressure and well geometry within a failure model.
6. Correlate rock strength, breakouts and cavings analysis to wellbore stability problems.
7. Determine the wellbore stability mechanism (e.g. tensile failure, shear failure, shale and mud chemical effects).
8. Determine in-situ stress estimates, and relate them wellbore stability indicators.

Wellbore Stability Analysis
9. Through comparison, determine the most practical and effective modeling techniques such as elastic, elastoplastic, poroelastic and others.
10. Perform a theoretical pre-drill wellbore stability prediction for each well using the high-graded methods, then apply data available from drilling to simulate how predictions could be upgraded while drilling.
11. Perform a detailed wellbore stability analysis, using all available data, to establish each well’s definitive, or “actual”, geomechanical conditions.
12. Compare the pre-drill predictions to the definitive analysis to determine which method and failure criteria are most effective in predicting actual wellbore stability under varying key conditions, such as vertical and inclined holes, normal faulting and other faulting regimes, rubble zones and bedding planes.
13. For wellbore conditions where analytical methods are inconclusive, identify a suitable numerical modeling technique.

**Documentation and Communication of Findings**
16. Develop a curriculum and teach Wellbore Stability Prognosis schools for drilling engineers.
18. Create and maintain a password-protected Wellbore Stability website that contains results of the project.

**17. Principal Investigators**
All project principal investigators have extensive experience in predicting and analyzing wellbore stability in all parts of the world:

- William Standifird  Officer in charge
- AJ Rizvi  Project Manager
- Dr. Jon Zhang  Chief Project Geoscientist
- Dr. Xinpu Shen  Geomechanics Specialist
- Dr. Joel Gevirtz  Modeling Specialist
- Dr. Martin D. Matthews  Modeling Specialist
- Other consultants  As required to perform work under supervision

**18. Methodology Examples**
Below are graphic examples of current practice for wellbore stability modeling. Integration of the best of such approaches is one of the main objectives of this project, along with improvements in the methods.
Figure 3–Inclination and azimuth of wellpaths through a formation, showing well inclination and the effect of drilling direction on the required mud weight.

Figure 4–The required mud weight and shear failure gradient in a well for different inclinations at a depth of 5000 m. Black dot in each plot shows the planned well path.
Figure 5–A pre-drill recommendation for mud weight to avoid instability in an inclined wellbore.

Figure 6–Wellbore failure modes related to pressure differentials.
Figure 7–Pore pressure distribution adjacent to a wellbore under drilling conditions, obtained from poroelastic modeling
Figure 8–Wellbore spalling prediction, obtained from FEM modeling
Figure 9–FEM mesh depicting vertical stress induced by a downhole cavity.
Figure 10–Wellbore stability analytical results showing the caliper log and hole size in the left track; predicted failure in the middle track, and predicted pore pressure (PP), shear failure gradient (SFG), fracture gradient FG (ShG), overburden stress gradient (OBG), and wellbore stability events in the right track.
Figure 11–Shear failure prediction (in blue) made from analytical analysis of offset wells.