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Wellbore Stability in Deep Water—Handling Geomechanical Uncertainty

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Abstract

Drilling in deep water presents many challenges, not the least of which is selection of the appropriate mud weight and casing set points to reach the target. Because of the high risk and large uncertainty, drilling programs often err on the side of conservatism, which drives costs up. This paper presents several examples of the application of geomechanical analysis using both deterministic and statistical methods to quantify the risk associated with mud weights that are either too high (and lead to lost circulation) or too low (and lead to wellbore collapse). The specific parameters that contribute the most uncertainty are determined by propagating all of the input uncertainties through the analysis. Once the parameters that contribute the most uncertainty have been identified, this knowledge in turn makes it possible to determine the amount of risk reduction that can be achieved by acquiring the data necessary to reduce the uncertainty of any or all of the input parameters.

Introduction

Drilling problems are often caused by wellbore instabilities that are due to compressive failure of the wellbore, which occurs as a direct result of the stress concentration that develops when drilling a well into an already-stressed rock mass. The parameters controlling these wellbore instabilities are the in situ stresses (the overburden, Sv; and the greatest and least horizontal stresses, SHmax and Shmin), the pore pressure (Pp), and the rock strength. If these parameters can be estimated, it is possible to predict the mud weight below which the well will collapse (the collapse pressure) and above which lost circulation will occur (the lost circulation pressure). In the general case, both the collapse pressure and the lost circulation pressure are controlled by the pore pressure, the orientations and magnitudes of the in situ stresses, the rock strength, and the wellbore orientation. Uncertainties in any of these parameters will result in uncertainties in predictions of the collapse and fracture pressures.

A number of sources of data can provide information about the in situ stresses, the pore pressure, and the rock strength. The vertical stress can be computed by integrating the weight of the overburden; density logs or local density-depth profiles provide the necessary input data. The pore pressure in shales can be estimated from compaction analysis using seismic velocity as an input; this provides a smooth initial profile which can be refined using velocity or resistivity logs. The least horizontal stress, which in deepwater environments is usually (but not always) the least principal stress, can be obtained from shut-in or closure pressure determined from extended leak-off tests. Rock strength can be estimated from velocity data; pre-drill estimates from seismic data require refinement using logs for the same reason this is necessary for pore pressure analysis. The remaining parameter, SHmax, the maximum horizontal stress, cannot be measured directly. The best way to constrain this parameter is from observations using image logs, which provide information on the occurrence and orientations of tensile wall fractures and the orientations and widths of breakouts. Quantitative techniques of wellbore stress analysis can then be applied using this data to constrain the magnitude of SHmax[1-5].

In many cases the stresses, pore pressure, and rock strength are poorly known, as the required data necessary to compute their values are often not available. Furthermore, models that describe the relationships between measured data and the required parameters are poorly calibrated. In some cases, technological or operational constraints make it impossible to acquire the information necessary to overcome these problems, resulting in considerable uncertainty in the parameters required to compute safe mud weights. Thus, it is valuable to utilize techniques to (1) predict the uncertainty in mud weight associated with uncertainties in all of the input parameters, and perhaps more important and (2) quantify for each parameter the benefit of spending the effort to reduce its uncertainty to a level which does not affect the predictions. Such techniques have been employed to quantify risk of wellbore collapse[6] but not to isolate those parameters that most contribute to the uncertainty of the results. The latter provides critical information to guide decisions about the benefit associated with collection of certain types of data compared to the risk of not collecting that data.

This paper addresses the above issues utilizing examples derived from experience addressing problems of geomechanical well design in a variety of deepwater environments. To simplify the discussion[*], we assume that the rock penetrated by the well is intrinsically isotropic (we do not consider the effect of weak bedding planes which can significantly affect wellbore stability[7,8]). We do not consider chemical interactions between drilling fluids and shales, nor do we consider poroelasticity or the effects of pore fluid or thermal diffusion[9]. Using the approach outlined in this paper, it is possible to determine for a given well design whether anisotropy or any of the other effects is important and if so, the extent to which uncertainties in the required parameters influence the results.

Causes of Wellbore Collapse and Lost Circulation

Wellbore collapse occurs due to excessive compressional failure of the rock at the wellbore wall. Compressive failure occurs wherever the wellbore stress concentration exceeds the rock strength and extends from the point of maximum compressive stress to the point where the stress concentration is just balanced by the rock strength. The angle over which the wellbore wall fails in compression is defined as the breakout width. Raising the mud weight generally increases the rock strength and decreases the compressive stress around the well, resulting in a decrease in breakout width. Decreasing the mud weight causes breakouts to become wider. As breakout width increases, larger amounts of cuttings are produced. Although the well will be stable for a finite breakout width, eventually the cuttings load becomes so large that it exceeds the carrying capacity of the mud system. When this occurs, either the penetration rate must decrease, hole cleaning must improve, or the mud weight must be increased to reduce the breakout width. If the mud weight is reduced too far, breakouts grow so wide that there is not enough intact rock to prevent the entire hole from collapsing; this condition cannot be mitigated by hole cleaning. However, provided an appropriate mud weight is maintained, breakouts themselves do not lead directly to hole collapse. This is both because breakouts do not grow wider once they have formed and, perhaps more importantly, even after breakouts begin to form, the rock within the breakout may still have some residual strength, and thus breakouts will eventually stabilize after achieving a finite depth[10-12]. Thus, there is a relationship between the initial width of a breakout and the volume of material produced, which is lithology-dependent. This relationship can allow computation of the excess cuttings volume due to the occurrence of breakouts of a certain width, from which it is possible to define for a given drilling system the limit beyond which breakouts will jeopardize hole stability. Overall, therefore, calculating the mud weight appropriate to contain compressive failure requires knowledge of the hole cleaning capabilities of the drilling system, whereby the costs of better equipment must be traded off against the costs associated with the requirement to use a higher mud weight if hole cleaning is inadequate (e.g., shorter casing lengths, greater risk of lost circulation, reduced penetration rates).

Lost circulation pressure is ultimately controlled by the least principal stress. This is because in order to lose mud it is generally necessary to create and propagate a hydraulic fracture. Fracture propagation requires a pressure equal or slightly in excess of the least stress (S3). However, in order to initiate lost circulation, a fracture must be created at the wellbore and propagated through the near-wellbore stress concentration so that it can “link up” with a far-field fracture. Either of these processes may require a pressure that is higher than the least stress. The initiation and link-up pressures are functions of all three stresses and of the orientation of the well[13]. If the static mud weight is higher than S3 but lower than the initiation and link-up pressures, it is possible to maintain circulation under ordinary circumstances. However, total lost circulation may occur without warning if there is a sudden increase in mud pressure, for example, due to pack-off or surge or while circulating out a kick. Thus, it is critical to determine not just leak-off pressure, but also S3 through use of an

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[*] The software used to carry out the stress and stability analysis and to generate the figures used in this paper provides models for these effects.

extended leak-off test that provides a measure of the shut-in or fracture closure pressure.

Effect of Stress State on the Relative Stability of Wells as a Function of Orientation

One approach to drilling design is to utilize the mud weight used to drill a previous well along with "rules of thumb" to predict the mud weights required to drill new wells. This approach can allow determination of approximate mud weights for inclined wells if mud weights used to drill nearby vertical wells are known. An example of the application of this approach to a deepwater environment is illustrated in Figure 1. This figure shows two different predictions of the mud weight required to drill a well as a function of the well orientation. The predictions are made for a well in deep water at a depth of more than 10,000 feet TVDSS. In the lower hemisphere projection utilized to display these wellbore stability diagrams, a vertical well plots in the center and inclined wells plot at increasing distances from the center. The concentric circles indicate 30 and 60 degrees deviation; horizontal wells plot at the outer edge of the diagrams. Wells deviated to the north plot towards the top, wells deviated to the east plot to the right, wells deviated to the south plot towards the bottom, and those deviated to the west plot to the left. The arrows show the orientation of the greatest horizontal stress (in this case, E–W; normal faults active in this stress field would be oriented N–S). In this analysis we assume that in order to maintain stability, it is necessary to keep breakouts from extending more than 90 degrees on each side around a vertical well and 40 degrees on each side around a horizontal well.

The stress state utilized to compute the required mud weights shown in the left-hand figure (Figure 1a) relies on shallow-water density profiles to compute the vertical stress. The pore pressure was computed from seismic velocity data. The least stress is at the limit below which normal faulting would occur, consistent with an assumption that this is an active extensional environment. Finally, it was assumed that the two horizontal stresses are equal. The resulting stress state is one in which both horizontal stresses are much less than the vertical stress (i.e., Shmin = SHmax << Sv). The results predict that the required mud weight to maintain stability increases significantly (from slightly less than 13 ppg for a vertical well to more than 14.5 ppg for a horizontal well) as deviation increases, but is independent of wellbore azimuth. This is a direct consequence of the assumption that the two horizontal stresses are equal and much less than the vertical stress. Furthermore, mud weights in excess of the least principal stress are required for wells with deviations above 60 degrees.

Figure 1b illustrates the predictions taking into account a number of additional data acquired while drilling a vertical well using the mud weights predicted by the above model. The vertical well was drilled with only minor problems, but data acquired in that well indicated that the stress state used to predict that mud weight was wrong. Sv was re-computed using an integrated density log and a value slightly lower than the earlier estimate was determined. On the other hand, higher leak-off pressures than were expected were measured and shut-in pressures provided direct measurements of Shmin that confirmed that it was larger than the original estimate. Image data provided evidence of breakouts; no drilling-induced tensile cracks were detected. Together, these data allowed constraint of the maximum stress, its orientation, and the rock strength. A stress state in which Shmin < Sv < SHmax resulted (a "strike-slip" faulting stress state, which is consistent with the location of this deepwater field in a "toe thrust" environment). The resulting analysis of mud weights correctly predicts the drilling experience in the vertical well, as did the previous model. But, it results in a much different picture of the required mud weights for inclined wells. An increase in mud weight of only 0.65 to 1.0 ppg above that used to drill the vertical well is required for horizontal wells, compared to an increase of more than 1.5 ppg for the previous stress state. Also, wells deviated in the SHmax direction require 0.35 ppg less mud weight than wells deviated perpendicular to SHmax. The much lower required mud weights predicted by this analysis make it possible to drill wells of any orientation, including horizontal wells.

Effect of Uncertainty on Casing Design for a Vertical Well

In many deepwater environments, offset data from previous wells are rare, either because there has been no previous drilling, because the new well is designed to drain a single deep target remote from other targets, or because the new well is drilled in an area of the field separated by faulting from that penetrated by previous wells. In many such cases, pre-drill data along the well path is restricted to seismic structural and velocity analyses.

Figure 2a shows an example pre-drill well design for a vertical well drilled into the center of a large fault block in which no other wells have been drilled. In this case, the pore pressure profile was inferred from seismic velocity data and the fracture gradient from offset well leak-off pressures. Because of uncertainties in both estimates, the choices of casing depths and mud weights were made using a model in which the upper bound pore pressure was assumed to be 0.5 ppg higher than the best estimate and the lower bound fracture gradient was assumed to be 0.5 ppg lower than a line approximately drawn through the minimum offset leak-off values. This ensures at least a 1 ppg mud window for all but the first two casings (Figure 2a). In order to reach TD given these design constraints, six casings are required.

The mud window of 1 ppg was justified based on the perceived uncertainty in the values of pore pressure and fracture gradient. However, another reason for the use of such a large window as a general practice is that minimum mud weight is limited not only by the pore pressure but also by the requirement to maintain an excess mud weight above the pore pressure to prevent collapse. Seen in this light, one way to reduce the uncertainty in the minimum required mud weight is to determine the collapse pressure.

In order to compute the collapse pressure it is necessary to determine the rock strength and horizontal stress magnitudes. Fortunately, rock strength can be estimated from seismic velocity. An upper bound for the collapse pressure in a vertical well can then be computed, assuming that the least horizontal stress is equal to the shut-in pressure from previous leak-off tests and that the maximum horizontal stress is close to the vertical stress computed from the weight of the overburden. This results in a new constraint on the lowest safe mud weight.

Figure 2b shows the mud window predictions for the original casing program determined using these new data. It requires that the lower limit of the mud window must be greater than both the pore pressure and the collapse pressure computed as above. At shallow depth, a mud pressure only slightly above the inferred pore pressure appears to be sufficient. But the collapse pressure is considerably higher than the pore pressure in the interval covered by the third and fourth casing strings. This effectively reduces the mud window for these casings to 0.6 ppg and 0.2 ppg, respectively, indicating a substantially greater risk of drilling problems for these intermediate casings.

Figure 2c presents an example of a new casing program that takes advantage of the additional information provided by the estimated wellbore collapse pressure. This design was produced by honoring the casing setting depth of the first string, and then requiring that each subsequent interval maintain a 0.5 ppg mud window between the collapse pressure and the fracture gradient. This results in a casing program that only includes five casing strings, in comparison to the previous program which required six. The smaller mud window is justified as it includes as a constraint the mud weight required to prevent collapse.

This result still has a large uncertainty due to the uncertainties in the values of the input parameters. Neither the rock strength nor the magnitudes of the horizontal stresses are known with certainty. Thus, the predicted collapse pressure is also uncertain; this will impact the likelihood of the casings reaching their planned depths. Of particular importance is the setting depth of the second string. To analyze the impact of these uncertainties on the setting depth for this string, we employ a statistical technique that utilizes Monte Carlo simulations of the mud weight required to keep breakouts small enough to avoid drilling problems at this depth.

Figure 3a shows the result of the analysis of the required mud weight to maintain stability at the bottom of the second casing string, presented in terms of the cumulative likelihood of success (in this case, success is interpreted as keeping breakouts smaller than a design width) as a function of mud weight. Ten thousand simulations of the stability of the well at this depth were computed, using parameters that were extracted randomly from a statistically meaningful distribution of the input values. For a mud weight of approximately 9.5 ppg, which is the lower bound of the mud window for the second casing string predicted using the deterministic analysis shown in Figure 2c, only slightly more than 1/4 of these simulations predicted a breakout width that was smaller than the required value—given the values and uncertainties in the input data. This suggests that the deterministic analysis was optimistic, and that it is unlikely that the second casing string could reach its design depth unless the effective mud weight were higher than this value. For example, a mud weight of 9.79 would provide an 86% likelihood of success (shown by the dashed line in the figure).

A number of variables contribute to the uncertainty in the above analysis. In order to investigate which of these is the most critical, Figure 3b presents a sensitivity plot of the relationship between required mud weight and each parameter, holding the others fixed. As can be seen, the known uncertainty in the vertical stress has no influence on the results. Variation in the vertical stress between 11.8 and 13.2 ppg equivalent results in no change in the 9.79 ppg mud weight required to stabilize the well. Similarly, the uncertainty in the minimum stress also has a relatively small impact on the required mud weight, as the range of uncertainty in Shmin between 10.8 and 12.0 ppg only results in a very small (~0.1 ppg) change in the required mud weight. Uncertainties in the magnitude of the maximum stress could require an increase in mud weight to 10 ppg or allow a decrease in mud weight to 9 ppg. Uncertainties in the rock strength contribute uncertainties of +0.05/–0.55 ppg. In both cases, the 9.79 ppg mud weight is at the high end of the required range. The range of possible pore pressures could require either a 0.25 ppg higher, or allow a 0.25 ppg lower, mud weight than 9.79 ppg. Thus, it appears that while the uncertainties associated with uncertainties in the rock strength and in SHmax are large, they may not be as critical to reaching this casing point as might at first be assumed, and a mud weight of 9.8 ppg is sufficient to reach the target depth.

Handling Uncertainties in Upper and Lower Bounds of the Mud Window

Figure 4 shows a set of casing plans for an inclined well drilled into a field in which excellent data are available from offset wells, including pore pressure from LWD data and least principal stress data from shut-in and fracture closure pressures at several depths. Thus, a high degree of confidence was placed on the derived pore pressure and fracture gradients. A planned casing program for this well is shown in Figure 4a. This program was designed utilizing a 1 ppg mud window between the pore pressure and the fracture gradient, with the expectation that this deviated well might require higher mud weights than previously drilled vertical wells. Four casings are required, assuming the first string can be placed at approximately 5,000 feet, to honor these design constraints.

Figure 5 shows not only the pore pressure and least principal stress gradients, but also the collapse gradient (determined based on stress constraints from previous drilling experience and a lower bound strength estimate derived from offset data) and the pressures required to initiate and to link up hydraulically induced fractures at each depth. Because they are a function of the well orientation, the collapse, fracture initiation, and linkup pressures shown in this figure were computed specifically for the proposed trajectory. When the wellbore collapse curve is included in the analysis, it is clear that there is a considerable risk that the second casing string will not reach its design depth (Figure 4b). This is because the minimum mud weight to prevent collapse at the bottom of the interval (10.19 ppg) is larger than the constraint imposed by the 10.16 ppg least stress at the previous casing shoe. Figure 5c shows an alternative casing design that places the bottom of the second casing string at 6,600 feet. This appears to be drillable, but the mud window for this second string is still extremely small (less than 0.25 ppg).

The model used to derive the predictions in Figure 4c still contains considerable uncertainty, particularly in the values of the rock strength and the maximum horizontal stress. To determine if there is a sufficient mud window to land the second casing string at its design depth, it is necessary to examine the effect of uncertainties in these parameters and in the pore pressure, the least stress, and the overburden by conducting Monte Carlo simulations of the critical mud weights. This requires running simulations at the top and bottom of the interval. At the bottom of the interval, we determine the likelihood of success as a function of mud weight required to prevent collapse. For this analysis we also consider whether allowing larger breakouts can lead to more favorable conditions. This provides input to decisions on whether to increase the carrying capacity of the mud system. To investigate the effects of uncertainty in the upper limit of the mud window, we evaluate the mud weight above which lost circulation would occur at the previous casing shoe. It is necessary to run the Monte Carlo simulations at both depths to establish the uncertainty in the mud window.

Figure 5a shows, at a depth of 6,600 feet, the likelihood of preventing wellbore collapse (based on keeping the widths of wellbore breakouts small enough that the excess cuttings can be safely removed from the well) and lost circulation [*], as a function of the effective mud weight. The borehole collapse prediction indicates that, for the model parameters, a mud weight of 10.1 ppg (highlighted by the vertical dashed line) is required to provide a 76% chance of avoiding collapse. Lower mud weights below 9.9 ppg are associated with a virtual certainty of collapse (less than a 25% chance of success). Examination of the sources of the uncertainties (Figure 5b) indicates that to improve confidence in the prediction, it is necessary to reduce the uncertainties in the pore pressure, the rock strength, and the maximum horizontal stress. Uncertainties in the minimum stress and the vertical stress do not significantly influence the results. Importantly, improved circulation that can allow drilling with wider breakouts only helps a little, as at best it allows the mud weight to be reduced by only 0.1 ppg.

Figure 6 shows the cumulative likelihood of collapse and lost circulation risks as a function of mud weight at the previous casing seat. The lost circulation pressure at this depth must be higher than the collapse pressure at the next casing seat shown in Figure 5. Figure 6a illustrates that the mud weight of 10.1 ppg required to provide a 76% chance of success at 6,600 feet is associated with a 40% chance of lost circulation at the previous shoe. Figure 6b shows that the largest source of uncertainty in this prediction is due to the uncertainty in the value of the least horizontal stress, Shmin. The lack of sensitivity of the leak-off pressure to any of the other parameters indicates that the only thing necessary to reduce the uncertainty in the safe upper bound mud weight for the second casing is to reduce the uncertainty in S3 by conducting an extended leak-off test at the first casing shoe.

Discussion

The above examples illustrate the importance of knowing the magnitudes of the in situ stresses, the pore pressure, and the rock strength. Furthermore, they show that if it is possible to define the uncertainties in these parameters, it is possible to use that knowledge to define uncertainties in the predictions of required mud weights to drill wells. Once these are defined, it is then possible to identify the parameters that contribute the most uncertainty and to develop a targeted program of measurements to reduce risk in a cost-effective manner.

In some cases, relative stabilities are sufficient to guide decisions. For example, the first case demonstrated that accurate knowledge of the relative stress magnitudes provides information that can be used to assess the feasibility of extended-reach drilling in a deepwater environment. In that example, the initial model indicated that extended reach wells could not be drilled. Further analysis utilizing data acquired in a vertical exploration well resulted in a revised prediction that demonstrated that extended reach drilling was possible.

Where it is necessary to quantify rock strength or pore pressure while a well is being drilled, LWD measurements can provide the necessary data. For example, resistivity and/or velocity data can be used to refine a pore pressure profile and to reduce its uncertainty. Measurements of acoustic velocity provide information to constrain rock strength. However, these LWD logs are not always designed to operate in the large holes required for the first few casing sections of deepwater wells. Thus the information must be acquired using wireline logs, which adds significantly to the cost and the risk associated with acquiring the data. The analysis carried out for the second example revealed that while there were substantial uncertainties in the predictions which could have been reduced by carrying out a comprehensive logging analysis program, it may be cost-effective, given the possible benefit, to acquire the data necessary to reduce those uncertainties.

The final example shows that acquisition of good leak-off test data, including a careful determination of shut-in or fracture closure pressure, can be extremely valuable. This is because it allows a quantitative assessment of the risk associated with raising mud weight to address hole instabilities where it is not possible to acquire the data necessary to reduce uncertainties in the collapse pressure. It also indicates that increasing the carrying capacity of the mud system does not always decrease the risk of collapse enough to justify the extra cost for that reason alone. In this case, the fact that the uncertainty in the predicted mud weight had multiple sources means that considerable additional effort would have to be devoted to improving the predictions,

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[*] The lost circulation risk provides a target pressure for the leak-off test should casing be set at this depth.

including the acquisition of real time data to improve the model while the well is drilled.

Nomenclature

SHmax = Maximum horizonal stress
Shmin = Minimum horizontal stress
Sv = Vertical stress; overburden
Pp = Pore pressure
S3 = Least principle stress
TD = Total depth penetrated by a well
LWD = Logging while drilling
ppg = Equivalent mud weight in pounds per gallon

Acknowledgments

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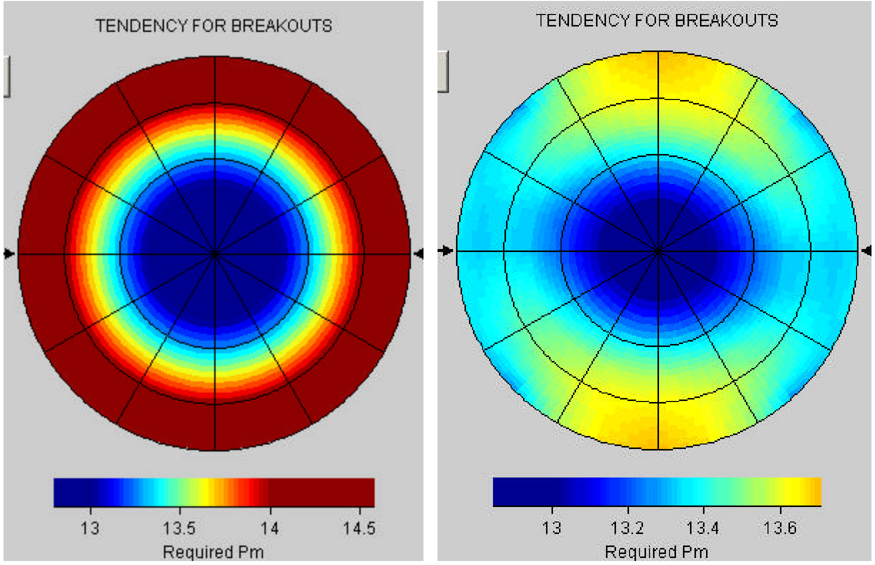
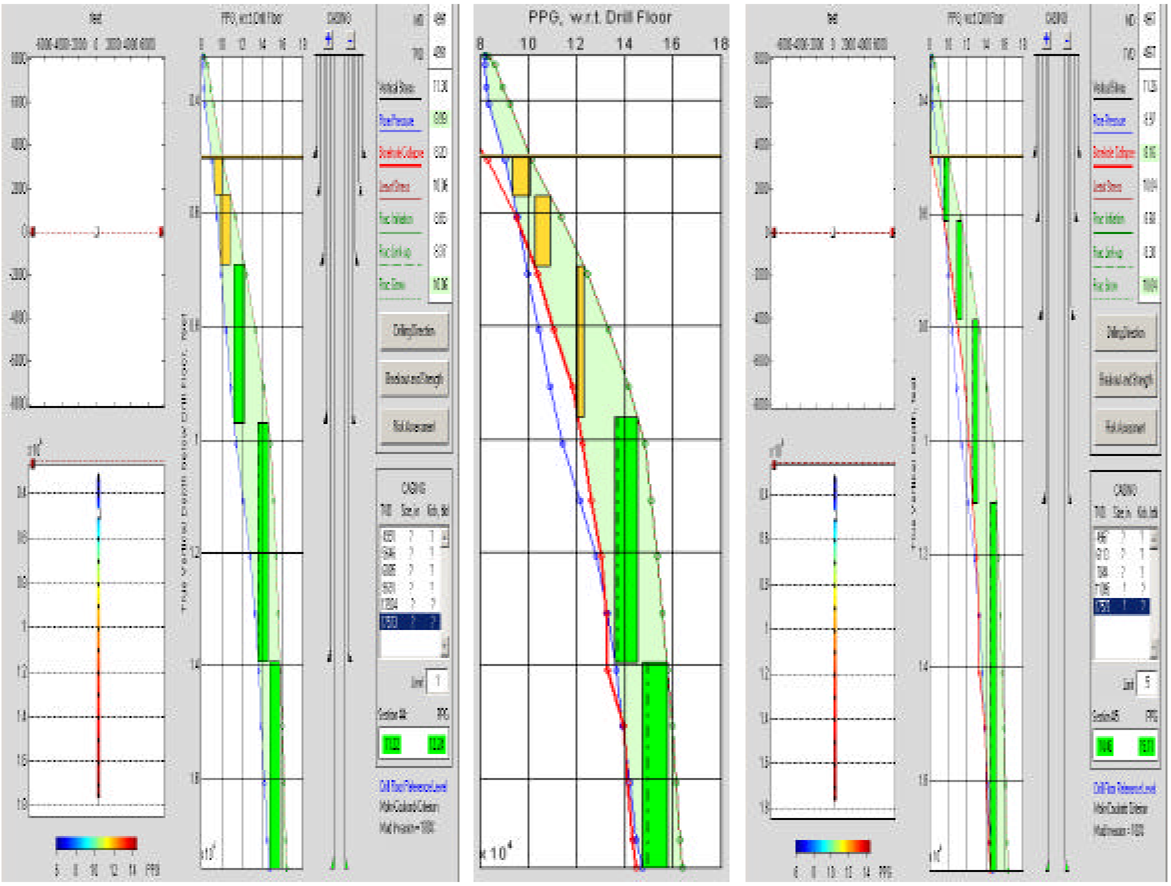
Figures



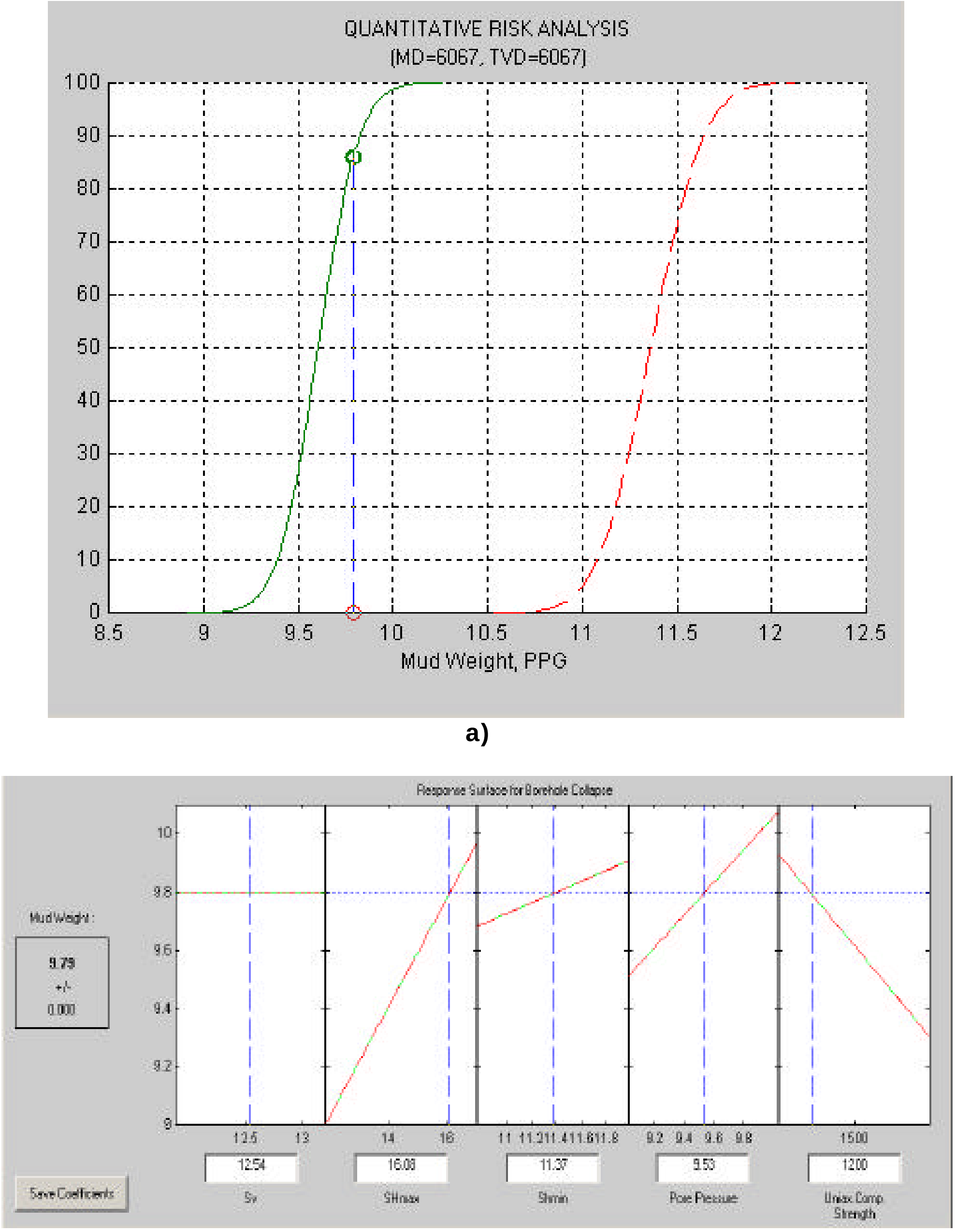
a) b)

Figure 1. Relative stability of wells in deep water at a depth of more than 10,000 feet TVDSS, as a function of orientation, for two different stress states. (a) Shmin = SHmax << Sv. (b) Shmin < Sv < SHmax.



a) b) c)

Figure 2. (a) Original casing design for a vertical well in deep water, showing mud weight windows designed using Pp + 0.5 ppg, and FG – 0.5 ppg. (b) Revised mud windows for the original program, which include the wellbore collapse pressure (shown in red). (c) An alternative casing program that honors the collapse and fracture gradient constraints and provides a 0.5 ppg mud weight window throughout.



a)

Mud Weight : 9.79 +/- 0.000

Sv 12.54

SHmax 16.08

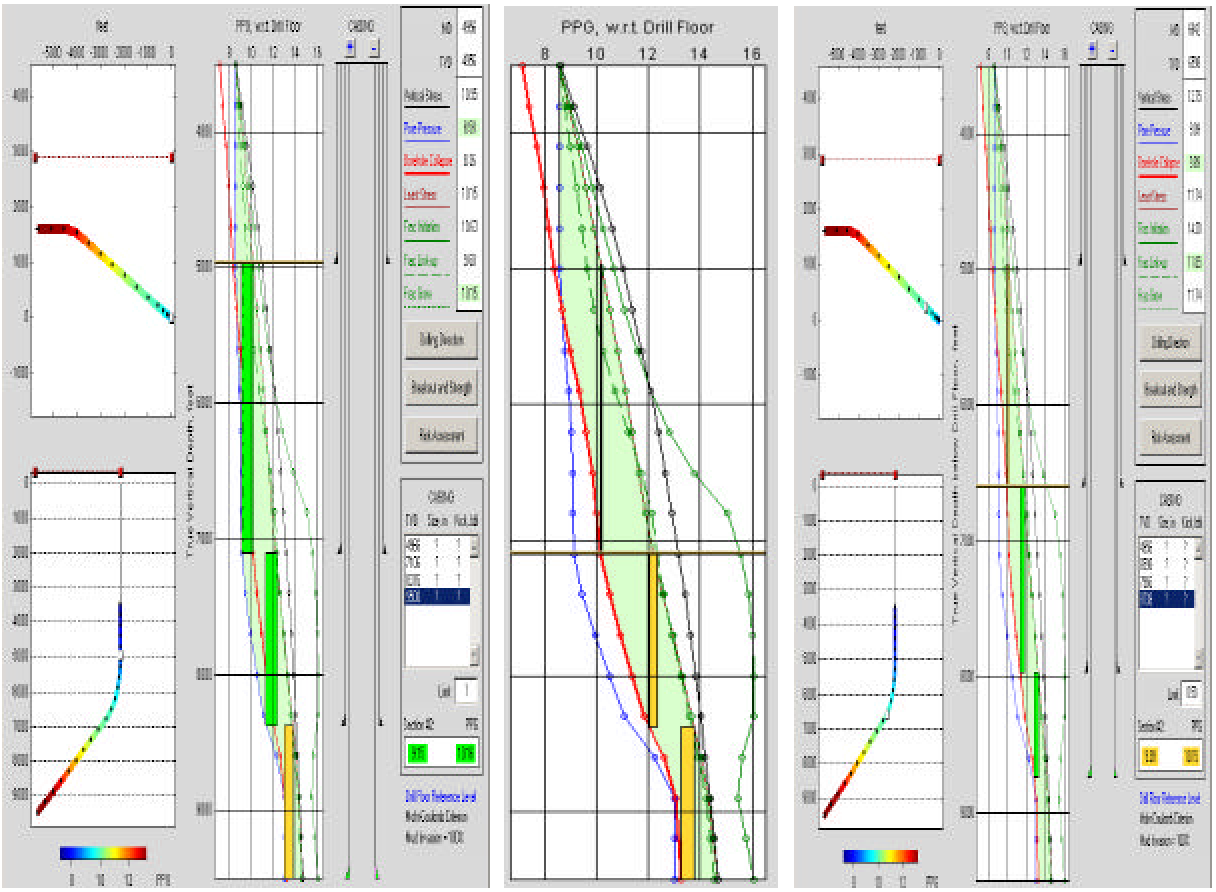
Shmin 11.37

Pore Pressure 9.53

Uniax Comp Strength 1200

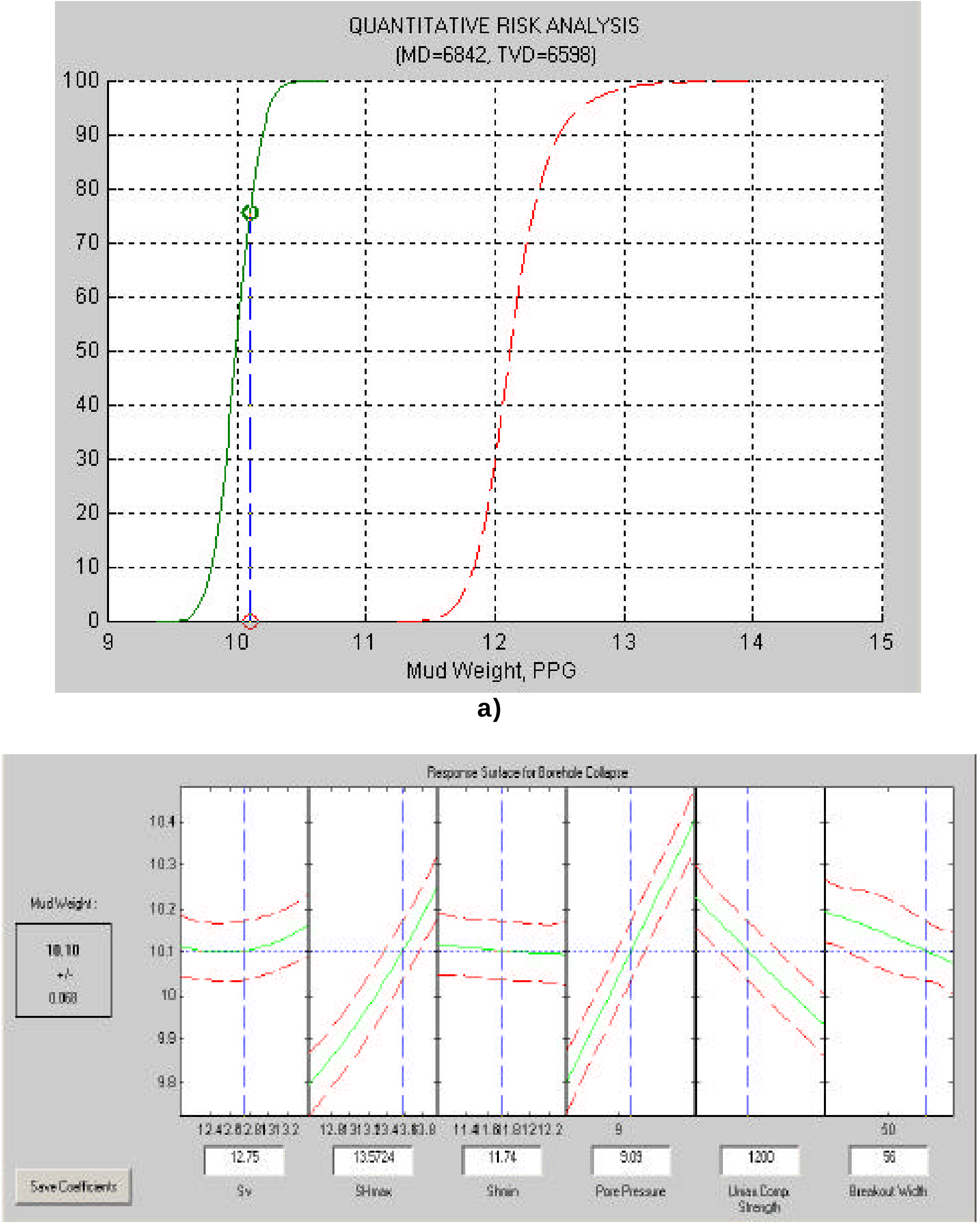
b)

Figure 3. (a) Analysis of the uncertainty associated with the collapse pressure at the bottom of the second casing string for the vertical well shown in Figure 2, which shows the cumulative probability of avoiding collapse (solid red) and causing lost circulation (dashed green). (b) Effect of uncertainties in the input parameters on the resulting mud weight predictions (The parameters investigated in this analysis are as follows: Sv: vertical stress; SHmax: maximum horizontal stress; Shmin: minimum horizontal stress; Pore pressure; and Uniaxial compressive strength).



a) b) c)

Figure 4. (a) Well plan for a deviated well showing casing set points utilizing a 1 ppg mud window between the pore pressure and fracture gradient. The depth of the first string is fixed. (b) Predicted mud windows for this casing program which include the collapse pressure. (c) An alternative casing program that reduces the length of the second string to allow a wider mud window, resulting in the requirement to set one additional string prior to reaching TD.



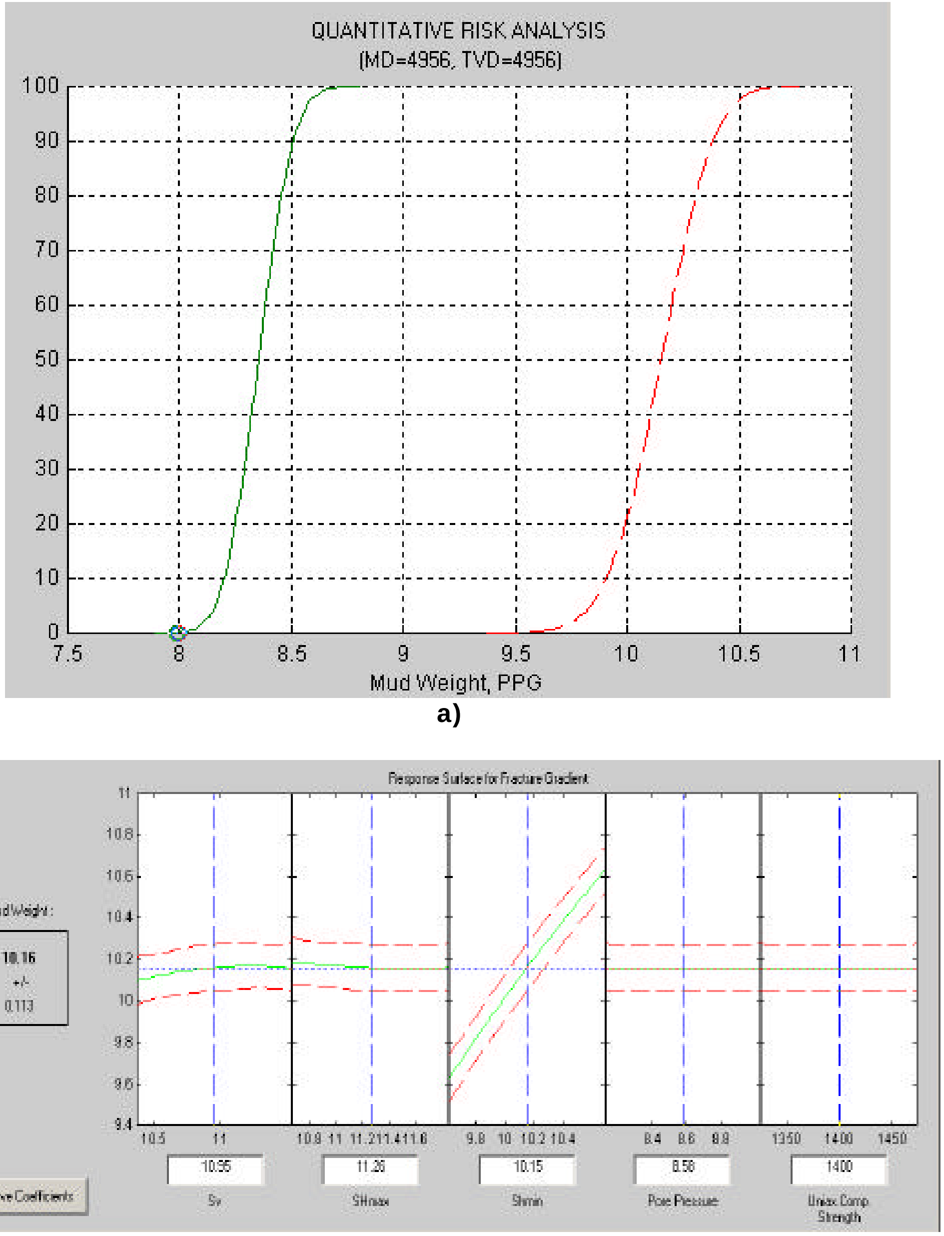
a)

Mud Weight :
10.10
+/-
0.068

Sv: 12.75
SHmax: 13.5724
Shmin: 11.74
Pore Pressure: 9.09
Uniax Comp. Strength: 1200
Breakout Width: 56

b)

Figure 5. (a) Analysis of the uncertainty associated with the collapse pressure at 6600 feet for the inclined well shown in Figure 4, which shows the cumulative probability of avoiding collapse (solid red) and causing lost circulation (dashed green). (b) Effect of uncertainties in the input parameters on the resulting mud weight predictions (The parameters investigated in this analysis are as follows: Sv: vertical stress; SHmax: maximum horizontal stress; Shmin: minimum horizontal stress; Pore pressure; Uniaxial compressive strength; Breakout width).



a)

Mud Weight:
10.16
+/-
0.113

Sv: 10.95
SHmax: 11.26
Shmin: 10.15
Pore Pressure: 8.58
Uniax Comp Strength: 1400

b)

Figure 6. (a) Effect of mud weight on the likelihood of lost circulation (red dashed line) at the first casing point for the inclined well shown in Figure 4. (b) The only source of uncertainty in the leak-off pressure is the least principal stress, Shmin.