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Assessment of Zonal Isolation Risk

to Changes in Design Parameters

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Assessment of Zonal Isolation Risk
to Changes in Design Parameters

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Report

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Dedication

To my most loving and caring parents

Zhenxin Zhang and Yuxiang Bao

To my beloved fiancé

Tianheng Feng

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Abstract

Assessment of Zonal Isolation Risk to Changes in Design Parameters

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The Well Containment Screening Tool (WCST) focuses on well integrity evaluation after well control incident. The WCST favors a greater wall thickness and, hence, a narrower cementing annulus, potentially increasing the risk of cement loss. We develop a structured and systematic physical model to simulate and track formation damage. A simulation process is conducted to assess the sensitivity of zonal isolation risk as design parameters are changed. In this paper, a physical model involving wellbore, casing and cement fluid is developed to understand the interaction between cement fluid and the formation. Two failure metrics are defined that provide a comprehensive understanding of the zonal isolation risk. Quantitative risk assessment is implemented with Monte Carlo simulation to assess the risk of zonal isolation problems when design parameters are changed. Models of production casing and intermediate casing are studied to verify the generality of this analysis. Taking both failure metrics into consideration, sensitivity analysis for models of production casing and intermediate casing present

common observations regarding changes of design parameters. Our analysis suggests that minor increases (within 0.05”) in casing thickness, due to increased outer diameter, has little influence on the risk of cement loss, as does slight decreases in mean open hole diameter (within 0.05”). To verify the generality of this approach, in addition to casing and wellbore parameters, the sensitivity to cement fluid flowrate is analyzed. We find that risk is not significantly affected by small increase of flowrate (e.g. from 40 to 100 gpm). This paper applies a novel quantitative risk analysis to assess the influence of different design parameters on zonal isolation problems. This approach, if well implemented, can help to assess the impact of changes in design parameters (e.g., casing length and depth, mud density and cement fluid density, etc.) on drilling safety. It can also help to inform drilling decisions by providing forecasts of zonal isolation risk for particular geological condition.

Table of Contents

List of Tables x

List of Figures xi

Chapter 1: Introduction 1

1.1 Well Containment Screening Tool 1

1.2 Quantitative Risk Assessment on Wellbore Stability 3

Chapter 2: Modeling Method 6

2.1 Overall Model Structure 6

2.2 Casing Model 7

2.3 Formation Model 8

2.3.1 Model Description and Inputs 8

2.3.2 Calculation Process 10

2.4 Hydraulics Model 11

2.5 Simulation Process 11

2.5.1 Monte Carlo Simulation 11

2.5.2 Generate Correlated Random Variables 12

2.5.3 Simulation Process 13

2.5.4 Sample Calculation 15

Chapter 3: Model Case Study and Results 17

3.1 Production Casing 17

3.1.1 Case Description and Inputs 17

3.1.2 Sensitivity Analysis Result and insights 18

3.2 Intermediate Casing 23

3.2.1 Case Description and Inputs 23

3.2.2 Sensitivity Analysis Result and Insights 25

Chapter 4: Conclusion..29

Reference 30

List of Tables

Table 1: Level 1- Screen Tool Sample Results..2

Table 2: Level 2- Screen Tool Sample Results..3

Table 3: Formation Model and Input..9

Table 4: Input for All Casing Models..18

Table 5: Input for Production Casing Model...18

Table 6: Input for Intermediate Casing Model...24

Table 7: Formation Model and Input for Open Hole Area of Intermediate Casing Model..25

List of Figures

Figure 1: Overall Model Structure 7

Figure 2: Sample of Failure 8

Figure 3: Flow Chart of Simulation Process 15

Figure 4: Sample Calculation...16

Figure 5: Plan View of Production Casing Model 18

Figure 6: How changing the Casing Diameter affects cement loss statistics. *Q = 145 gpm*, μ_{doh} *= 8.5", doc = 7.0" ~ 7.5", (Annulus = 0.5" ~ 0.75")* 19

Figure 7: How changing the Open Hole Diameter affects cement loss statistics. *Q = 145 gpm*, μ_{doh} *= 8.0"~ 8.5", doc = 7.0", (Annulus = 0.5" ~ 0.75")*...20

Figure 8: How changing the Flow Rate affects cement loss statistics. *Q = 40 ~ 250 gpm*, μ_{doh} *= 8.5", doc = 7.3" (Annulus = 0.6")*.................................20

Figure 9: How changing the Open Hole and Annulus affects cement loss statistics. *Q = 145gpm*, μ_{doh} *= 6.5"~ 10.5" (Annulus = 0.5" ~ 0.75")* 21

Figure 10: How changing the Flow Rate and Casing Diameter affects cement loss statistics. *Q = 40 ~ 250 gpm*, μ_{doh} *= 8.5" (Annulus = 0.5"~ 0.75")* ..22

Figure 11: How changing the Open Hole and Flow Rate affects cement loss statistics. *Q = 145 gpm*, μ_{doh} *= 6.5" ~ 10.5" (Annulus = 0.75")* 23

Figure 12: Plan View of Intermediate Casing Model 24

Figure 13: How changing the Casing Diameter affects cement loss statistics. *Q = 145gpm*, μ_{doh} *= 8.5", doc = 7.0" ~ 7.5"*..26

Figure 14: How changing the Open Hole Diameter affects cement loss statistics. *Q = 145gpm*, μ_{doh} *= 20.0", doc = 16 ~ 16.8" (Annulus = 2 ~ 1.6")* 26

Figure 15: How changing the Flow Rate affects cement loss statistics. *Q = 145gpm,* μ_{doh} *= 16.5 ~ 20", doc = 16" (Annulus = 0.25 ~ 2")* 27

Figure 16: How changing the Flow Rate and Casing Diameter affects cement loss statistics. *Q = 40 ~ 250 gpm,* μ_{doh} *= 2, doc =16~16.5" (Annulus = 2 ~ 1.75")* 28

Chapter 1: Introduction

1.1 Well Containment Screening Tool

After the Macondo event, industry efforts to date seems to have gravitated to being reactive. They focus more on blowout recovery issues rather than preventing the blowout. Tools and improvements are all developed to deal with well integrity during blowout conditions. Well Containment Screening Tool (WCST) is one of these tools which doesn't address the likelihood and prevention of blowouts. As a joint industry task force, WCST was established to develop an evaluation tool to demonstrate if a well design and equipment is adequate for well containment. It analyzes the wells mechanical and geologic integrity to determine which of the 3 following categories the well falls into:

1. Full mechanical and geologic integrity.
2. Mechanical or geologic integrity not intact, but consequence of failure is acceptable.
3. Wellbore integrity does not exist and well cannot be shut-in without hydrocarbons escaping or broaching to sea.

The WCST consists of two levels. Level 1 WCST is designed to expedite approval for wells that can be fully shut-in without causing underground flow using very conservative assumptions and simple calculations. Two load cases are analyzed:

1. Collapse during uncontrolled flow to seafloor.
2. Burst after shut-in with a full hydrocarbon gradient.

Information needed includes:

1. General Well Information.
2. Offset Well Information.
3. Well Design and Casing Plan Information.

4. Productive Formation Information.

Two analyses are done in Level 1. Formation Integrity Analysis is a section that analyzes the deepest exposed shoe as well as any other potential loss zones in open hole to determine if there will be underground flow when the well is shut-in. The other is Mechanical Integrity Analysis which consists of Burst Analysis, Trapped Annulus Screening and Collapse Analysis. Level 1 has four outputs in total. Their acceptance criteria and sample checking results are listed in Table 1. If a well does not pass all 4 of the level 1 criteria, then a level 2 is required for that hole interval.

Screening Tool Level 2 Results	
Formation Integrity Below Deepest Exposed Shoe	PASS
Burst Integrity	PASS
Trapped Annuli Check	PASS
Collapse Integrity	PASS

Table 1: Level 1- Screen Tool Sample Results

Level 2 WCST uses offset data and more advanced calculations to mitigate the probability of the failures identified in level 1. If the failure cannot be mitigated or eliminated, then a consequence analysis is performed to see if failure is acceptable. Level 2 analysis tool and summary table use the term “primary string” and “second string”. Primary string are strings that are exposed to the flow from the reservoir, assuming no strings have failed. A second string is a string that becomes exposed when a primary string fails. Level 2 WCST is based on the Level 1, with the following modified or additional calculations:

1. Annulus pressure buildup for trapped annuli.
2. Secondary string collapse and burst verification.
3. Formation strength verification for failed strings.

Level 2 has five outputs whose acceptance criteria and sample checking results are listed in Table 2.

Screen Tool Level 2 Results	
Formation Strength Verification Below Deepest Shoe	PASS
Burst Integrity - Primary Strings	PASS
Collapse Integrity – Primary Strings	L2 Formation Integrity and/or Second String Verification Required
Secondary String Verification	PASS
Formation Strength Verification for Failed Strings	PASS

Table 2: Level 2- Screen Tool Sample Results

We can easily see that the WCST only focuses on well integrity evaluation after the blow-out occurs. In this sense, a key feature of the tool is that it favors stronger casing strings with larger wall thickness. This might help to hold the shut-in pressure in blowout condition, but may increase the blowout risk of the whole system. The main reason is that thicker casing wall will result in tighter casing-formation and casing-casing annuli. It may increase the cement failure risk and cause the zonal isolation problem.

1.2 Quantitative Risk Assessment on Wellbore Stability

Primary cementing is the process of placing cement in the annulus between the casing and the formations exposed to the wellbore. After drilling the well to the desired depth, the drill pipe is removed and a larger string of casing is run into the well until it reaches the bottom of the well. At this time, the drilling mud used to remove formation cuttings during drilling the well is still in the wellbore. This mud must be removed and replaced with hardened cement. Sufficient cement is pumped into the casing to fill the annular column from the bottom up to at least across the productive zones. The well is left shut in for a time to allow the cement to harden before beginning completion work or drilling out to a deeper horizon (Nelson, 1990).

The primary objective of primary cementing is to provide zonal isolation (Smith, 1987). It protects groundwater aquifers, and isolates producing and non-producing zones for optimal production. Ideally, the cement fluid pressure and mud pressure should always be between pore pressure and fracture pressure of formation. The fluid pressure needs to be large enough to balance the pore pressure and prevent contamination. At any part of open hole, if pressure of cement fluid exceeds the fracture pressure of the formation, fluid will flow into one or more geological formations instead of returning up the annulus. It is called loss circulation. This case of cement failure will increase the risk of zonal isolation problem. Consequences of failure of zonal isolation can be as little as the loss of a few dollars of drilling fluid, or as disastrous as a blowout and loss of life. Therefore, assessing its risk is essential.

To consider the "real-world" variation of parameters instead of simplifying input variables from statistical range of data to a deterministic value in regular deterministic modeling approach, Quantitative Risk Analysis (QRA) has been presented in the last decades as a method to assess uncertainty associate with the input datasets. The basic process is:

Step 1. Decide suitable distribution function for input parameters.

Step 2. Develop an appropriate constitutive model to relate the input parameters to desire output.

Step 3. Define a limit state function as threshold between failure and success.

Step 4. Specify a respond surface to obtain a likelihood of failure by quantifying uncertainty involved in estimation of input and output parameters using probabilistic distribution functions.

The last step can be done with an interactive numerical simulation method such as Monte-Carlo technique. Monte-Carlo simulation has been replaced by traditional deterministic methods in petroleum industry to quantify the uncertainty included in any input datasets (Gholami et al., 2015).

A large number of literature have reported the use of probability assessment in petroleum. Related applications was proposed since decades ago ranging from wireline operations (Sam et al., 1994), drilling exploratory prospects (Cowan et al., 1969), prediction of pore pressure and fracture gradient (Liang, 2002), optimum casing setting depth selection (Turley et al., 1976) and directional drilling (Thorogood et al., 1991), etc.. Application of QRA to oil and gas drilling area is introduced by Ottesen et al. (1999).

In drilling operations, a proper mud weight needs to be used in order to avoid wellbore instability. For wells with narrow drilling margin, the uncertainty of pore and fracture pressure and other relative parameters has been emphasized. Limited work relevant to application of probability assessment on wellbore stability has been down by Morita et al. (1995), Later, Ottesen et al. (1999), Liang (2002), Moos et al. (2003), Sheng et al. (2006), Aadnoy et al.(2011), Undegbunam et al. (2013), Gholami et al. (2015). They can be used as reference for studying cement loss problem. However, there are few studies on the application of influence of different design parameters on zonal isolation problem uncertain conditions. In this paper, we are going to develop a physical model to track positions of circulation-loss points along the cement area. QRA will be implemented with Monte Carlo simulation method to assess the risk of zonal isolation problem when design parameters are changed due to the WCST.

Chapter 2: Modeling Method

2.1 Overall Model Structure

During each drilling process, after installing the outer casing and finishing drilling deeper for the next casing, we put the next casing into the well and pump cement fluid to cement the annulus between the formation and the next casing. The cementing process is the process we are going to simulate. During this process, when the pressure of cement fluid exceeds the fracture pressure of the formation, the cement loss will occur at that place which increases the risk of zonal isolation. The system we look at consists of cement fluid, mud and annulus that fluid flow through and the annulus the cement fluid cements. Annular is formed by inner circle which is the casing and outer circle which may consist of casings or open hole. The outer circle depends on the depth and the drilling process.

Figure 1 shows the structure of our model. It consists of three physical models: Hydraulics Model, Casing Model and Formation Model. Control variables are fluid flow rate, outer-diameter of casing and the mean of open hole diameter. The output of Hydraulics Model and Casing Model is fluid pressure. The output of Formation Model is fracture pressure. Combining these two outputs, the objective output relevant to the failure matrix is calculated.

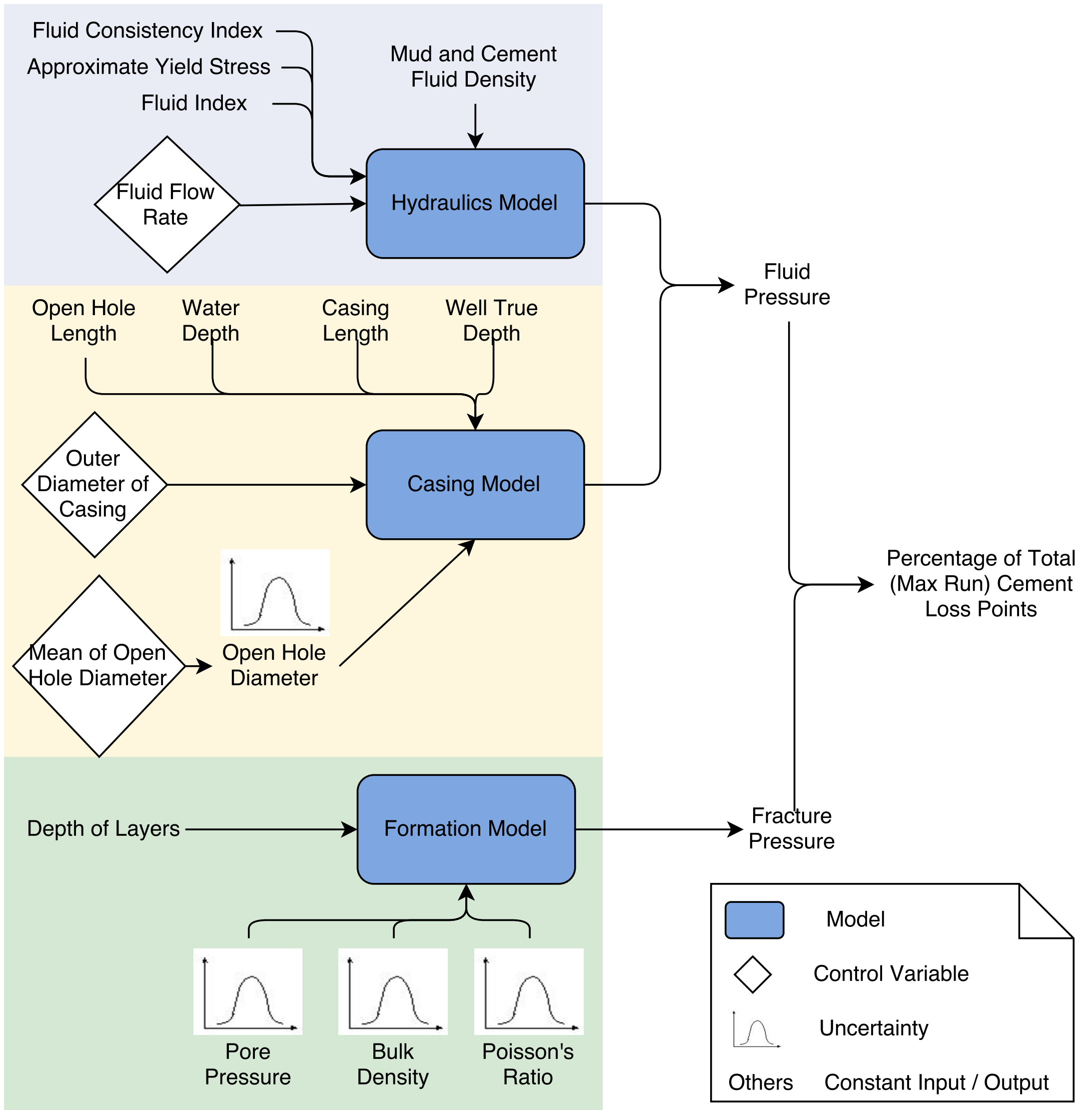

Figure 1: Overall Model Structure

2.2 Casing Model

Recall that we are looking at cement loss failures respect to zonal isolation, in that sense two particular failure matrix are defined. We discretize the whole open hole into finite elements, each subject to a maximum of one possible "cement loss point failure". The failure occurs when fluid pressure at that element exceeds the fracture pressure.

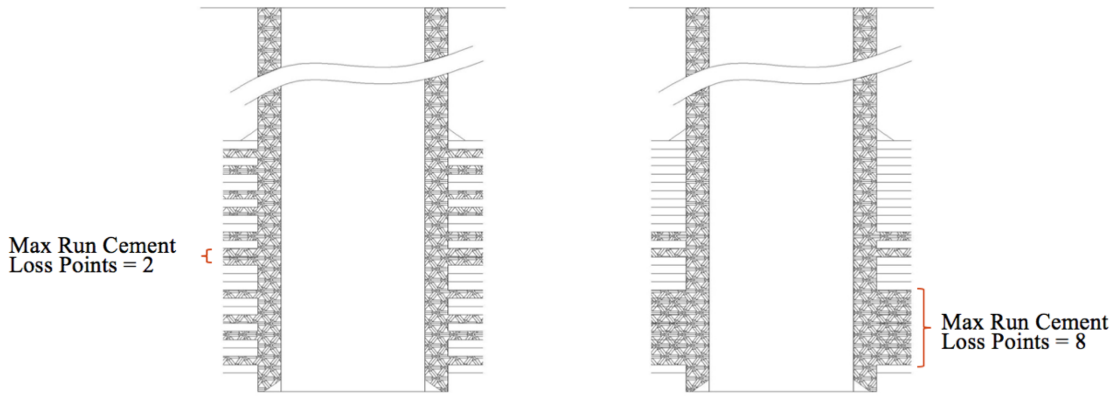

Figure 2: Sample of Failure

- Failure Matrix 1:

$$Percentage\ of\ Total\ Cement\ Loss\ Points = \frac{Total\ Cement\ Loss\ Points}{Total\ Number\ of\ Finite\ Elements} \quad (1)$$

- Failure Matrix 2:

$$Percentage\ of\ Max\ Run\ Cement\ Loss\ Points = \frac{Max\ Run\ Cement\ Loss\ Points}{Total\ Number\ of\ Finite\ Elements} \quad (2)$$

In Failure Matrix 1 we calculate the percentage of the failures occurs over the whole open hole area. Whereas in Failure Matrix 2, we calculate the longest run of failures that occurs over the entire open hole. Figure 2 shows two sample failure cases. These two cases have same percentage of total cement loss points which is 11/28 = 40%. But they have different percentage of max run cement loos points: 2/28 = 7% of the left case and 8/28 = 30% of the right case. Even their total cement loss points are the same, the right case faces greater risk respect to zonal isolation.

2.3 FORMATION MODEL

2.3.1 Model Description and Inputs

The Formation Model is used to predict fracture pressure for each finite element. According to Macondo data, the open hole area is mainly composed of two kinds of rocks: shale and sandstone which form eleven layers. Inputs of Formation Model are gradient of pore pressure, bulk density and Poisson's ratio. They are all treated as uncertainties. It's safe to assume that they follow the Normal distribution (Liang, 2002; Udegbunam et al., 2013; Adams et al., 1993). We assume that elements inside same layers have the same nature which means their uncertainties have the same distribution but samples for each element vary with each other. Pore pressure in each element is correlated with adjacent elements inside same layer but has high variation at boundaries of layers. Depth of each layer and corresponding inputs of Formation Model for Production Casing Case are listed in Table 3. To predict the fracture gradient, we also need to know fracture gradient at the top of open hole. Empty area inside the red box is the outputs. They will vary in elements not in layers, because samples of uncertainties are generated for each element.

Number	**Depth(ft)**	**Lithology**	**Gradient of Pore Pressure (ppg)**		**Gradient of Fracture Pressure (ppg)**	**Bulk Density (g/cc)**		**Poisson's Ratio**	
			Mean	**Std**		**Mean**	**Std**	**Mean**	**Std**
1	17000~17380	Shale	13.2	0.233	16	2.6	0.0667	0.33	0.0233
2	17380~17390	Sandstone	14.1	0.233		2.5	0.1	0.2	0.0067
3	17390~17490	Shale	13.2	0.233		2.6	0.0667	0.33	0.0233
4	17490~17500	Sandstone	13.1	0.233		2.5	0.1	0.2	0.0067
5	17500~17750	Shale	13.2	0.233		2.6	0.0667	0.33	0.0233
6	17750~17770	Sandstone	12.6	0.233		2.5	0.1	0.2	0.0067
7	17770~17800	Shale	13.2	0.233		2.6	0.0667	0.33	0.0233
8	17800~17880	Sandstone	12.6	0.233		2.5	0.1	0.2	0.0067
9	17880~17900	Shale	13.2	0.233		2.6	0.0667	0.33	0.0233
10	17900~17920	Sandstone	12.6	0.233		2.5	0.1	0.2	0.0067
11	17920~18000	Shale	13.2	0.233		2.6	0.0667	0.33	0.0233

Table 3: Formation Model and Input

2.3.2 Calculation Process

Predicting fracture pressure is a challenging work, since its accuracy varies with different locations and formation properties. Various methods can be applied to estimate fracture pressure. Eaton's method (Eaton et al., 1969) is one of them which has relatively high degree of acceptance and can be used in a worldwide application because of its simplicity. Based on this method, we predict the fracture pressure by adding randomness in statistical ranges of uncertainties and the calculation process each element *j* is listed below.

Step 1. Sample uncertainties from normal distribution: Bulk Density ρ, Poisson's Ratio γ, Gradient of Pore Pressure *PG*. For the *PG*, we assume that there is a high correlation 0.8 inside layers and a twice standard deviation at each layer boundary.

Step 2. Overburden pressure for each element:

$$S_j = \rho e \times 0.433 \tag{3}$$

Step 3. Add up to get total overburden pressure OP_j for each element:

$$OP_j = \sum_{k=1}^{j} S_k + OP_0 \tag{4}$$

where OP_0 is overburden pressure on the top for the open hole (here is at 17,000 *ft*) and is back calculated based on the known fracture gradient at depth 17,000 *ft*.

Step 4. Effective vertical stress:

$$\theta_{vi} = OP_j - PP_j \tag{5}$$

where PP_j is pore pressure and is calculated from sample of *PG*.

Step 5. Fracture pressure:

$$FP_j = \frac{\gamma}{1-\gamma}\theta_{vi} + PP_i \tag{6}$$

2.4 Hydraulics Model

Equivalent Circulating Density (ECD) calculated in equation (7) is the effective density exerted by a dynamic circulating fluid against the formation that takes into account the pressure drop in the annulus above the point being considered. It is equal to the hydrostatic pressure of the mud column plus additional frictional pressure loss in the annulus above the point of interest.

$$ECD(\text{ppg}) = \frac{P_{Hydrostatic} + \Delta P_{Ann}}{0.052 \times TVD} \tag{7}$$

where *TVD* (*feet*) is the True Vertical Depth. It is the vertical depth from an interest point in the well to a point at the surface. We assume $P_{Hydrostatic}$ (*ppg*) is calculated based on fluid density and *TVD*, see equation (8). Other hydrostatic influences are not considered such as fluid compressibility, fluid thermal expansion, etc. $\Delta P_{Hydrostatic}$ (*ppg*) is frictional pressure loss in the annulus above the interest point (Section 2.4.2).

$$P_{Hydrostatic} = 0.052 \times \rho \times TVD \tag{8}$$

where ρ (*ppg*) is the fluid density. Hydraulics model and calculation process of annular frictional pressure losses ΔP_{Ann} we used are mainly from Guo and Liu (2011).

2.5 Simulation Process

2.5.1 Monte Carlo Simulation

Recall that the two failure matrices we are currently looking at are the percentage of total cement loss points and percentage of max run loss points. Cement loss points are positions where fluid pressure exceeds fracture pressure. Uncertainties are open hole diameter, gradient of pore pressure, Poissions' ratio and bulk density. Notations for *i*th element (from top of the open hole to the bottom) are

DOH_i = open hole diameter of *i*th element, for $i \in [1, I]$

PG_i= pore pressure gradient of *i*th element, for $i \in [1, I]$

PR_i = Poission's ratio of ith element, for $i \in [1, I]$

BD_i = bulk density of ith element, for $i \in [1, I]$

where I is the total number of finite elements from top of inner casing to the bottom of open hole we are looking at.

Thus we are facing a four dimensional uncertainty. Even we safely assume they all follow the normal distribution, the probability distribution of each failure matrix relative to the four-dimensional uncertainty is still too complex. Computing the mean is difficult, due to multidimensional integration. In this sense, provided availability of necessary computing power and required information, Monte Carlo simulation method can be applied. Its basic process is to generate samples of all the uncertainties from their known distribution and then calculate the objective matrix. After iterating sufficient times, we obtain large number of objective matrix. By taking the mean, we achieve an approximated value (Nowak and Collins, 2012).

2.5.2 Generate Correlated Random Variables

Recall that in Formation Model we assume that the pore pressure gradient PG_i of each element i has high correlation ($\beta = 0.8$) inside layers. It means that correlation coefficient between adjacent entries should equal to 0.8. Traditional process used to generate correlated normal random variables cannot be used since the covariance matrix is unknown. Below is the generation process we developed based on filtering principle.

Step 1. Let $X = [x_1, x_2, ..., x_I]$ be vector we generated using from standard normal distribution, where x_i are independent and $x_i \sim Normal\ (0, 1)$, $i \in [1, I]$.

Step 2. Create $Y = [y_1, y_2, ..., y_I]$ based on the difference equation (19) and (20) below.

$$y_i = \beta y_i - 1 + \sqrt{1-\beta^2}\, x_i, \forall i \in [2, \mathrm{I}] \tag{19}$$

$$y_1 = x_1 \tag{20}$$

We will proof that y_i follows standard normal distribution and correlation coefficient between adjacent entries satisfies $\beta_{y_i,y_{i+1}} = \beta$, $\forall i \in [1, I]$.

Step 3. Create objective sample vector, pore pressure gradient of each element: $PG = [PG_1, PG_2, ..., PG_I]$ using equation (21).

$$PG_i = \mu + \sigma y_i, \forall i \in [1, I] \tag{21}$$

where μ and σ are respectively the mean and standard deviation of pore pressure gradient of this layer. We assume that mean of pore pressure gradient of different elements inside the same layer remains a same constant number.

Proof: Using recursion method. Assume y_{i-1} ~ *Normal* (0,1) and we have x_{i-1} ~ *Normal* (0,1). According to the difference equation (19), we have

$$VAR(\mathrm{y}_i) = \beta^2 \times 1 + (\sqrt{1-\beta^2})^2 \times 1 = 1, \forall i \in [1, \mathrm{I}] \tag{22}$$

$$Mean(\mathrm{y}_i) = 0, \forall \mathrm{i} \in [1, \mathrm{I}] \tag{23}$$

Since $y_1 = x_1$ ~ *Normal* (0, 1), according to recursion, y_i ~ *Normal* (0, 1).

Then we calculate the correlation coefficient of y_{i-1} and y_i for $\forall i \in [2, I]$ in equation (24).

$$\beta_{y_i, y_{i-1}} = \frac{COV(\beta \mathrm{y}_{i-1} + \sqrt{1-\beta^2}\, \mathrm{x}_i, \mathrm{y}_{i-1})}{\sigma_{y_{i-1}} \sigma_{y_i}} = \beta COV(\mathrm{y}_{i-1}, \mathrm{y}_i) + \mathrm{COV}(\sqrt{1-\beta^2}\, \mathrm{x}_i, \mathrm{y}_{i-1}) = \beta \tag{24}$$

Thus the correlation between adjacent entries equals to constant β. The proof is complete.

2.5.3 Simulation Process

To assess each of the failure matrix, the simulation process consists of two nested loops. The inside loop is iterating for each finite elements from the top of cement annulus to the bottom of open hole. At each finite element and its corresponding depth, we calculate cumulative fluid pressure and compare it with the fracture pressure to see if cement loss occurs there. The outside loop is iterating for each group of sample data (generated for uncertainties). The simulation process for evaluating Failure Matrix 1 - Percentage of Total Cement Loss Points is listed below. The flow chart is shown in Figure 3. Flow Chart of Simulation Process.

Step 1. Generate sample data for uncertainties.

Step 2. Calculate ECD and then accumulative fluid pressure FLP_i at depth $i \times e$ using Casing Model and Hydraulics Model. Notation i means ith finite elements in open hole counting from top to bottom. Notation e is the length of each element.

Step 3. Calculate Fracture Pressure FP_i for each element in open hole area using Formation Model. If $i \times e$ is greater, then the length of the outer casing which means we are reaching the open hole area, we will go to Step 4. Otherwise we increase i by one and go back to Step 2.

Step 4. Calculate the limit state function.

$$g_i = FP_i - FLP_i \tag{25}$$

If $g_i < 0$, cement loss will occur in this element and total cement loss points T_j will increase by one. Then, if i reaches total number of finite elements I, go to step 5. Otherwise we increase i by one and go back to Step 2.

Step 5. Calculate the Failure Matrix 1- Percentage of Total Cement Loss Points.

$$p_j^1 = \frac{T_j}{I'} \tag{26}$$

where j means jth iteration of simulations and I' is the total number of finite elements in open hole area which is also the total possible cement loss points. If j reaches the total number of iterations J we set, we will go to Step 6. Otherwise we increase j by one and then go back to Step 1.

Step 6. Calculate the mean of all the p_j.

$$\mu_p^1 = \frac{\sum_{j\in[1,J]} p_j^1}{J} \tag{27}$$

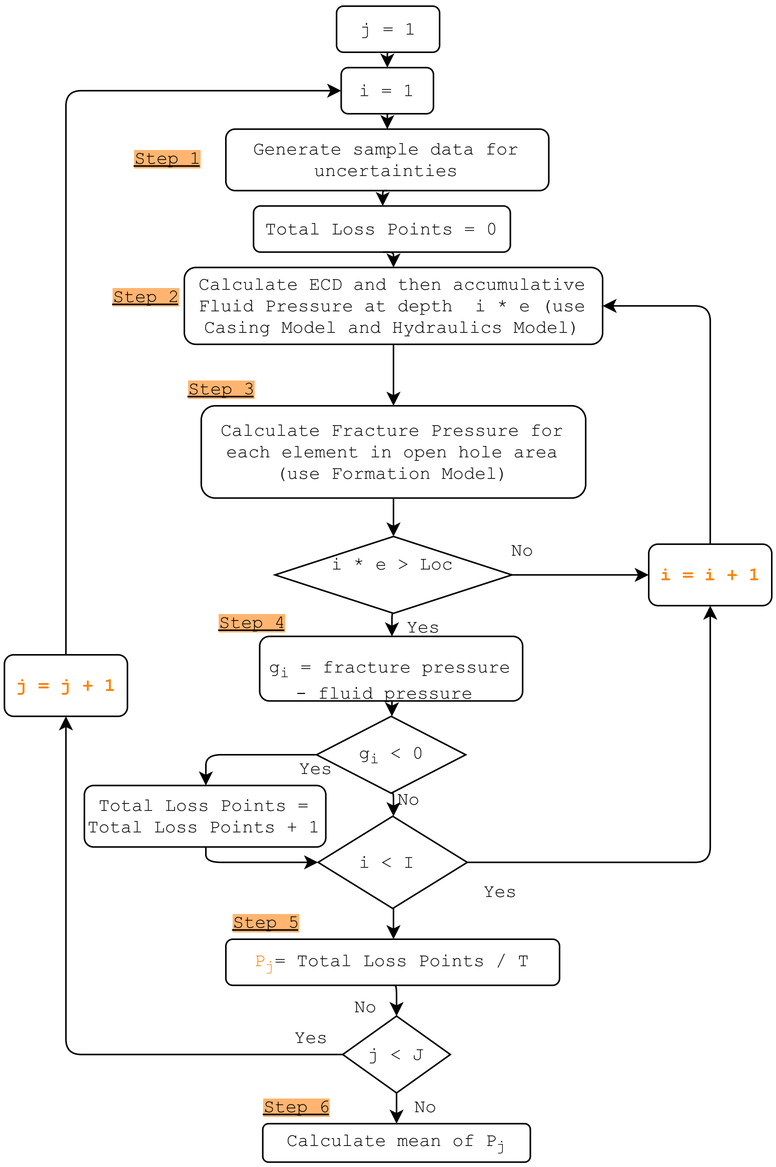

Figure 3: Flow Chart of Simulation Process

2.5.4 Sample Calculation

Figure 4 shows one sample calculation result. The inputs of control variables are:

Diameter of casing: $DOC = 7.1''$

Mean diameter of open hole: $\mu_{DOH} = 8.5''$

Flow Rate: $Q = 100\ gpm$

In this sample (jth simulating iteration), total cement loss points is $T_j^1 = 14$ and max run cement loss points is $T_j^2 = 8$. The numbers 1 and 2 in T represent Failure Matrix 1 and Failure Matrix 2. Given $I' = 100$, the percentage of total cement loss points $p_j^1 = 14\%$ and the percentage of max run cement loss points is $p_j^2 = 8\%$.

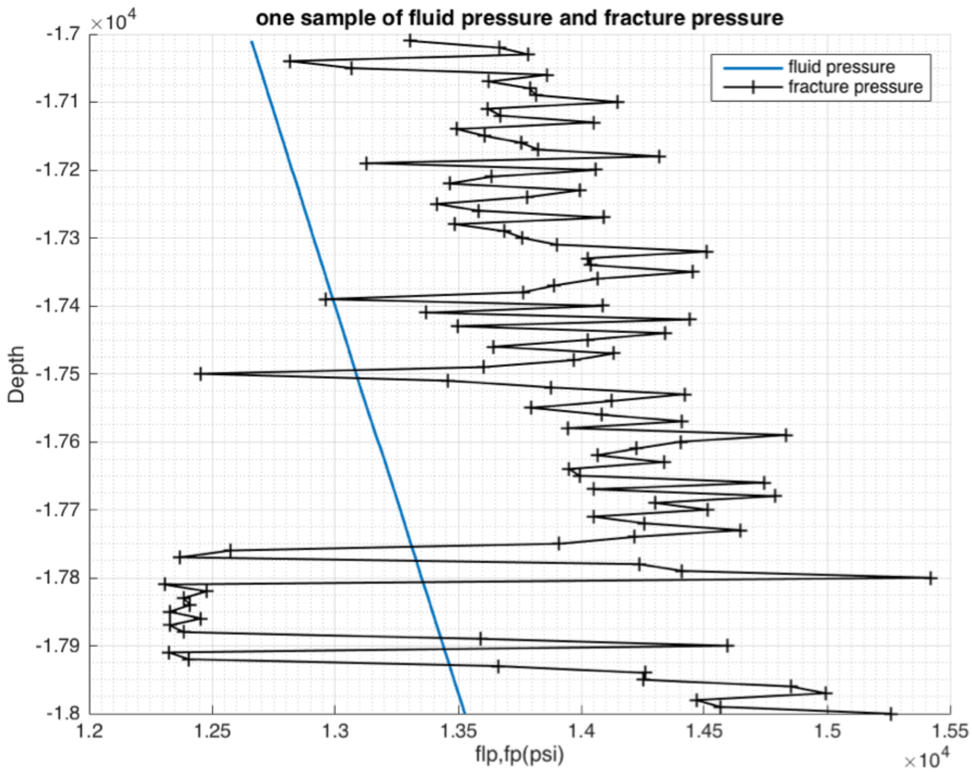

Figure 4: Sample Calculation

Chapter 3: Model Case Study and Results

The two casing models we are going to look at in this chapter are based on the Macondo Well. The production casing is formed by long string production casing, outer casing and the open hole. The intermediate casing is formed by 16" intermediate casing, 18" drilling linear, 22" surface casing and the open hole with mean diameter 20". We discretize the whole open hole into finite elements, each subject to a maximum of one possible cement loss point failure.

3.1 Production Casing

3.1.1 Case Description and Inputs

Production Casing Model is composed of outer casing, production casing and open hole. Fluid flows through two different annulus. Inner circle of these annulus is always the production casing. Bottom to top, outer circle is open hole and outer casing. Cement loss may occur in open hole-production casing annular. Figure 5 shows the plan view of the model. Table 4 lists inputs which will be used in all casing models. Table 5 lists input for the Production Casing Model.

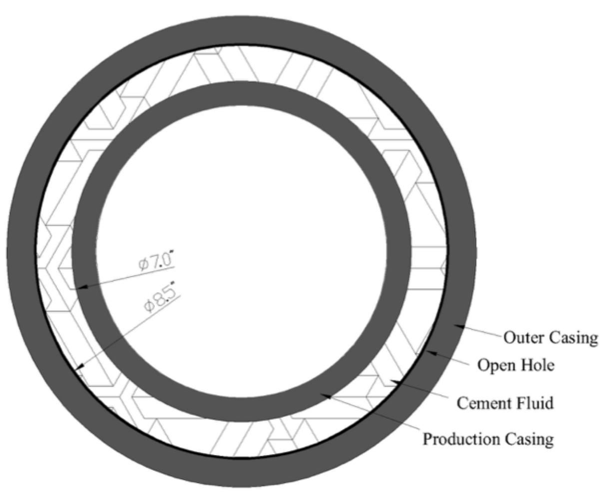

Figure 5: Plan View of Production Casing Model

Category	Input	Value
Cement Fluid	Density (ppg)	14
	Flow Rate (gpm)	40 - 250
Depth and Length (ft)	Well True Depth	18000
	Water Depth	5000
	Length of element	10
Herschel Bulkley Model	Fluid Consistency index	30
	Approximate Yield Stress	20
	Fluid Index	0.8

Table 4: Input for All Casing Models

Category	Input	Value
Production Casing	Length (ft)	13000
	Outer Diameter	7" (to 7.5")
Outer Casing	Length(ft)	12000
	Inner Diameter	8.5"
Open Hole	Length (ft)	1000
	Mean Diameter	(8" to) 8.5"
	Std of Diameter	0.17"

Table 5: Input for Production Casing Model

3.1.2 Sensitivity Analysis Result and insights

By changing control variables: Flow Rate Q, Mean Diameter of Open Hole μ doh and Casing Diameter doc, we obtain following sensitivity analysis results. Figure 6, Figure 7 and Figure 8 shows respectively how changing the Casing Diameter, Open Hole Diameter, Flow Rate affects cement loss statistics. From Figure 6, increasing outer diameter of casing from 7" to 7.2" (annulus width decreases from 0.75" to 0.65") doesn't result in large increase of percentage of cement loss points. The max run cement loss points almost stay the same. From Figure 7, decreasing mean of open hole diameter from 8.5" to 8.4" (annulus width decreases from 0.75" to 0.7") doesn't have much influence on percentage of cement loss points. The results are almost symmetric to the results of increasing casing diameter. From Figure 8, minor increase of flow rate will not have obvious influence on the percentage of failure. The percentage of max adjacent cement loss points remains in same low level when flow rate is in the lower half of the assumption range.

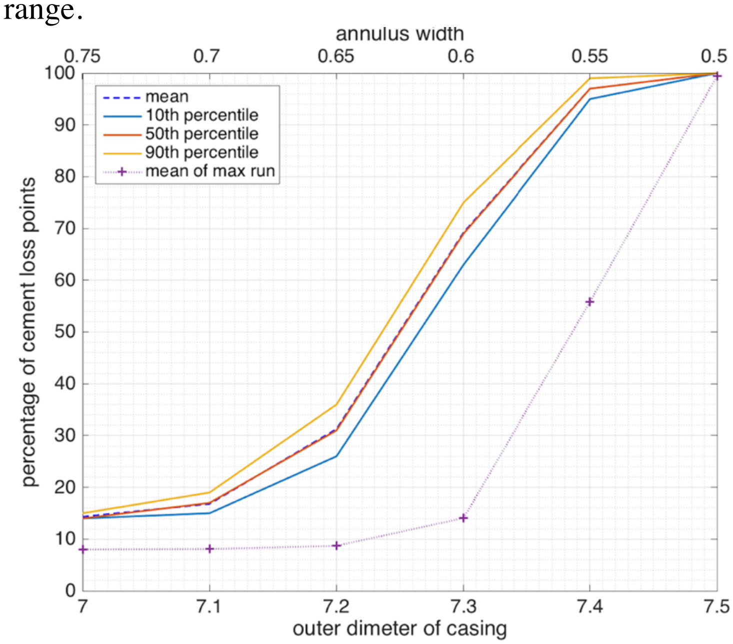

Figure 6: How changing the Casing Diameter affects cement loss statistics. *Q = 145 gpm*, μ_{doh} *= 8.5", doc = 7.0" ~ 7.5", (Annulus = 0.5" ~ 0.75")*

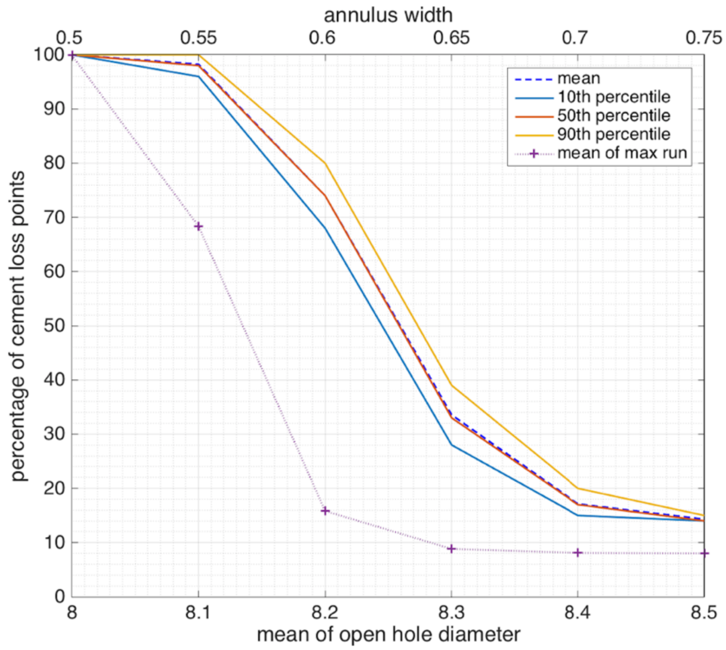

Figure 7: How changing the Open Hole Diameter affects cement loss statistics. *Q = 145 gpm*, μ_{doh} *= 8.0"~ 8.5", doc = 7.0", (Annulus = 0.5" ~ 0.75")*

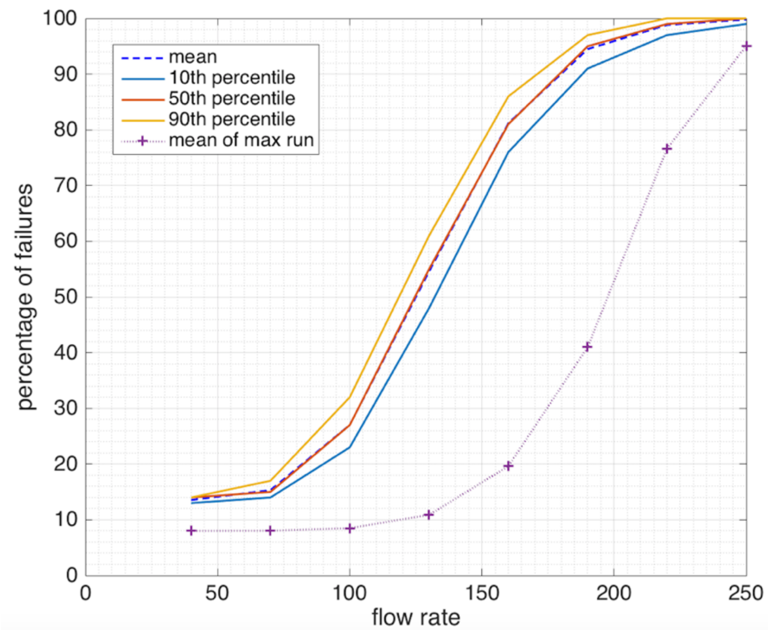

Figure 8: How changing the Flow Rate affects cement loss statistics. *Q = 40 ~ 250 gpm*, μ_{doh} *= 8.5", doc = 7.3" (Annulus = 0.6")*

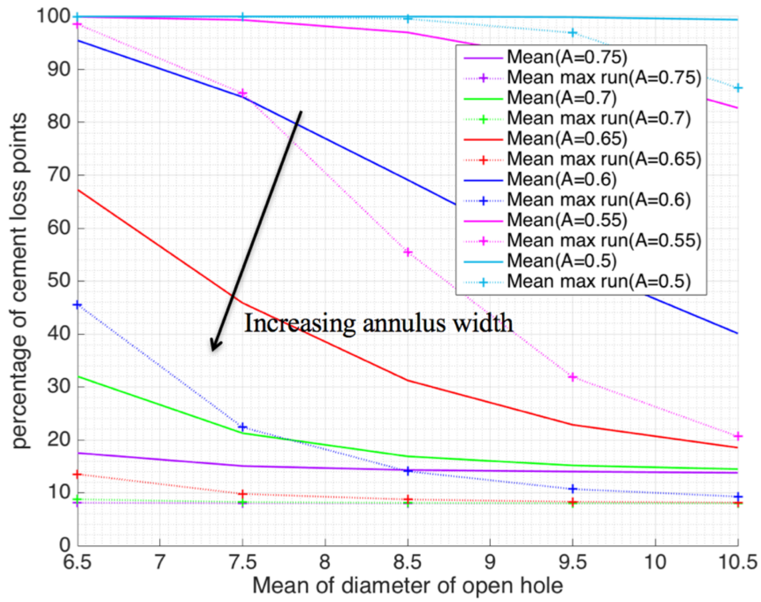

Figure 9: How changing the Open Hole and Annulus affects cement loss statistics. $Q = 145gpm$, $\mu_{doh} = 6.5" \sim 10.5"$ (Annulus = 0.5" ~ 0.75")

In order to obtain more comprehensive results, we change two control variables at the same time. Figure 9 shows how changing the Open Hole and Annulus affects cement loss statistics. In this case, we increase mean diameter of open hole and annulus at the same time. Multiple curves are generated by changing the diameter of casing based on desired annulus width. It shows that annulus width is not the only influence factor. The scale of the open-hole-and-casing system also affects the cement loss statistics. For relative small annulus width (dark blue and red curve), system with larger scale has obviously lower percentage of cement loss points and the percentage of max adjacent loss points decrease more rapidly, when system scale is increasing.

Figure 10 shows how changing the Flow Rate and Casing Diameter affects cement loss statistics. It shows that when flow rate is low (40 *gpm*), different annulus width all remain in lower percentage of cement loss points. As flow rate increases, cement loss statistics of system with smaller annulus width increase tremendously.

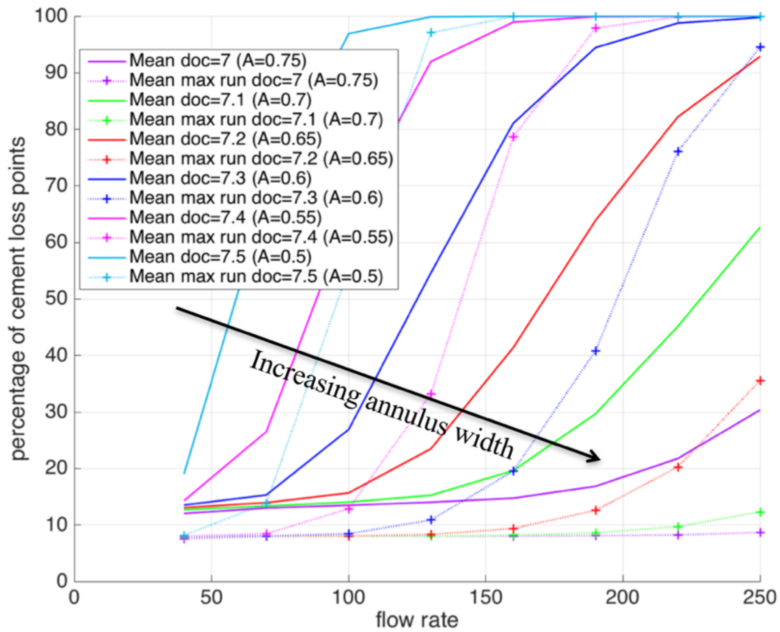

Figure 10: How changing the Flow Rate and Casing Diameter affects cement loss statistics. $Q = 40 \sim 250$ *gpm*, $\mu_{doh} = 8.5"$ *(Annulus = 0.5"~ 0.75")*

Figure 11 shows how changing the Open Hole and Flow Rate affects cement loss statistics. In this case, annulus width is fixed. Mean diameter of open hole and casing diameter are increased by the same amount. For system with larger scale, percentage of cement loss points are less sensitive to flow rate. The percentage of max adjacent cement loss points are much less sensitivity relative to percentage of cement loss points.

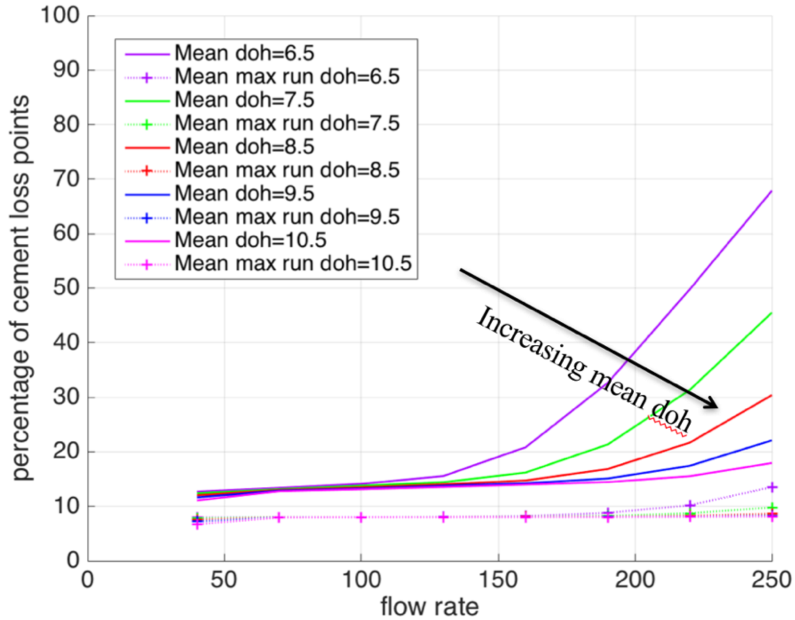

Figure 11: How changing the Open Hole and Flow Rate affects cement loss statistics. *Q = 145 gpm*, μ_{doh} *= 6.5" ~ 10.5" (Annulus = 0.75")*

3.2 Intermediate Casing

3.2.1 Case Description and Inputs

Intermediate Casing Model is composed of surface casing, drilling liner, intermediate casing and open hole. Figure 12 shows the plan view of the model. Fluid flows through three different annulus. Inner circle of these annulus is always the intermediate casing. Bottom to top, outer circles are open hole, drilling liner and surface casing. Cement loss may occur in open hole-intermediate casing annulus. Table 6 lists input for the model. Depth of each layer and corresponding inputs of Formation Model for Intermediate Casing Case are listed in Table 7.

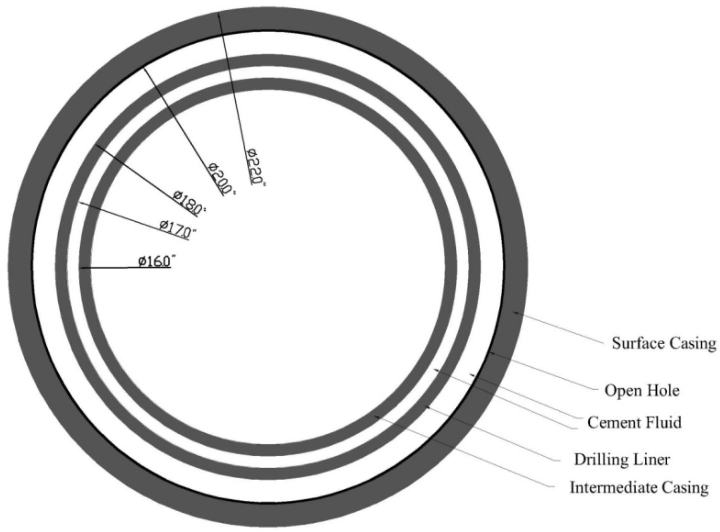

Figure 12: Plan View of Intermediate Casing Model

Table 6: Input for Intermediate Casing Model

Category	Input	Value
Intermediate Casing	Length (ft)	6600
	Outer diameter	16" (to 16.8")
Surface Casing	Length (ft)	3000
	Outter Diameter	22"
	Inner Diameter	20"
Drilling Liner	Length (ft)	1000
	Outter Diameter	18"
	Inner Diameter	17"
Open Hole	Length (ft)	2600
	Mean of Diameter	(16.5" to) 20"
	Std of Diameter	0.17"

Table 7: Formation Model and Input for Open Hole Area of Intermediate Casing Model

Number	Depth(ft)	Lithology	Gradient of Pore Pressure (ppg)		Gradient of Fracture Pressure (ppg)	Bulk Density (g/cc)		Poisson's Ratio	
			Mean	Std		Mean	Std	Mean	Std
1	9000~9010	Shale	11.1	0.233	12.55	2.6	0.0667	0.33	0.0233
2	9010~9030	Sandstone	11.1	0.233		2.5	0.1	0.2	0.0067
3	9030~10430	Shale	11.1	0.233		2.6	0.0667	0.33	0.0233
4	10430~10440	Sandstone	11.1	0.233		2.5	0.1	0.2	0.0067
5	10440~10550	Shale	11.1	0.233		2.6	0.0667	0.33	0.0233
6	10550~10560	Sandstone	11.1	0.233		2.5	0.1	0.2	0.0067
7	10560~11100	Shale	11.1	0.233		2.6	0.0667	0.33	0.0233
8	11100~11180	Sandstone	11.1	0.233		2.5	0.1	0.2	0.0067
9	11180~11200	Shale	11.1	0.233		2.6	0.0667	0.33	0.0233
10	11200~11280	Sandstone	11.1	0.233		2.5	0.1	0.2	0.0067
11	11280~11600	Shale	11.1	0.233		2.6	0.0667	0.33	0.0233

3.2.2 Sensitivity Analysis Result and Insights

By changing three control variables: Flow rate Q , Mean Diameter of Open Hole μ_{doh} and Outer Diameter of Intermediate Casing doc, we obtain following sensitivity analysis results. Figure 13, Figure 14, Figure 15 show respectively how changing the Casing Diameter, Open Hole Diameter, Flow Rate affects cement loss statistics. Results and insights are similar as the case of production casing.

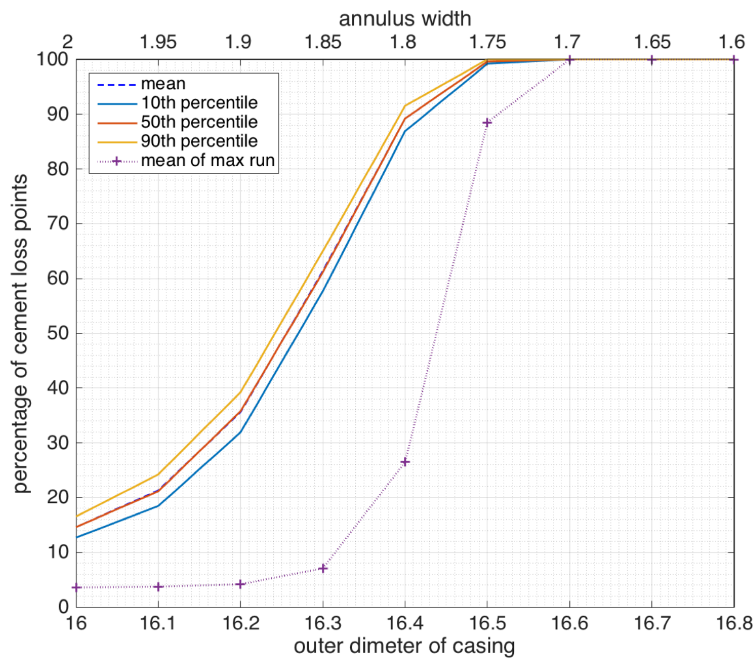

Figure 13: How changing the Casing Diameter affects cement loss statistics. *Q = 145gpm*, μ_{doh} *= 8.5", doc = 7.0" ~ 7.5"*

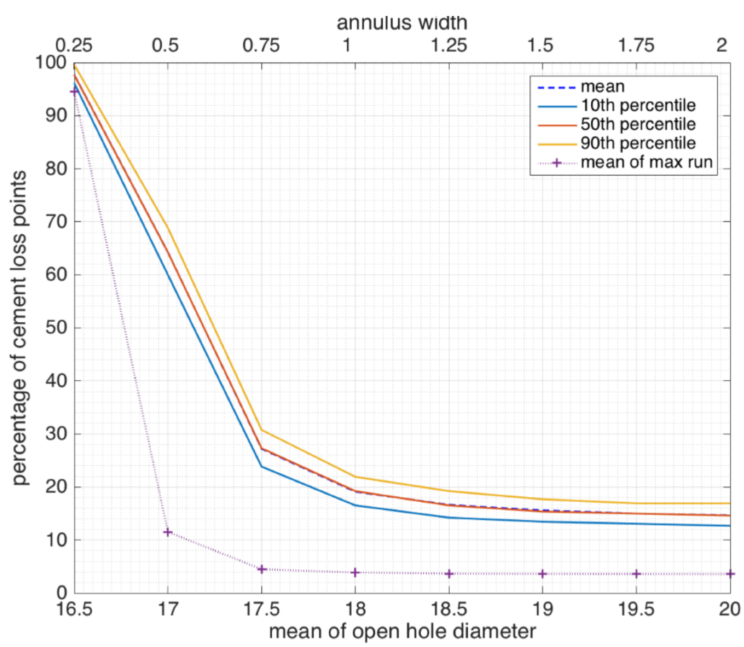

Figure 14: How changing the Open Hole Diameter affects cement loss statistics. *Q = 145gpm*, μ_{doh} *= 20.0", doc = 16 ~ 16.8" (Annulus = 2 ~ 1.6")*

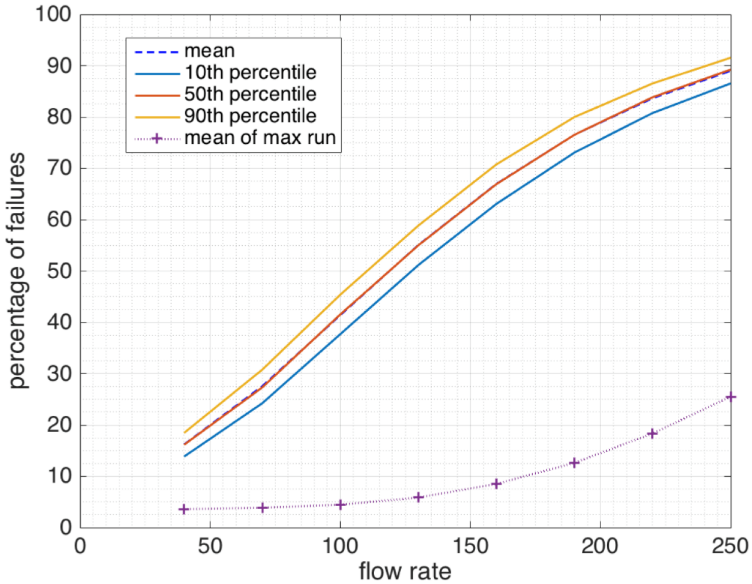

Figure 15: How changing the Flow Rate affects cement loss statistics. *Q = 145gpm*, μ_{doh} *= 16.5 ~ 20", doc = 16" (Annulus = 0.25 ~ 2")*

For more comprehensive results, Flow Rate and Casing Diameter are changed at the same time and its effect on cement loss statistics is shown in Figure 16. It shows that, when mean diameter of open hole is fixed, cement loss statistics of system with larger annulus width will be much less sensitive to flow rate.

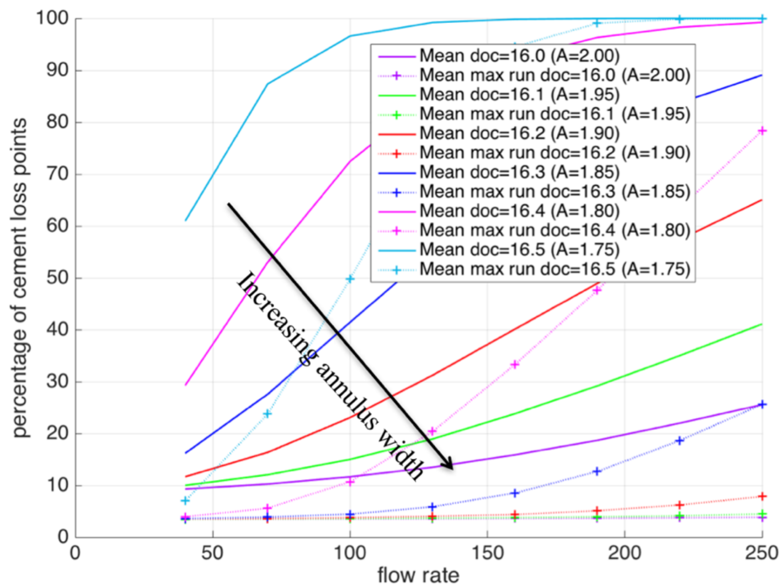

Figure 16: How changing the Flow Rate and Casing Diameter affects cement loss statistics. *Q = 40 ~ 250 gpm*, μ_{doh} *= 2, doc =16~16.5" (Annulus = 2 ~ 1.75")*

Chapter 4: Conclusion

This report presents a zonal isolation risk evaluation approach from a systematic point of view. A physical model is built to quantify interaction between cement fluid, casing and formation. It applies a novel quantitative risk analysis method to assess the influence of difference design parameters on zonal isolation problems. The analysis focuses on quantifying risk of a new offshore drilling regulation - Well Containment Screening Tool and demonstrate that minor increase (within 0.05”) of casing thickness by increasing outer diameter doesn’t have much influence on cement loss problem.

This analysis, if well implemented, can also help to assess the risk of cement loss problem for changes of other design parameters like open hole diameter, flow rate, mud or cement fluid choose, etc., among which sensitivity of open hole diameter and flow rate are assessed in this paper. It shows that annulus width is not the only influence factor. The scale of the open-hole-and-casing system also affects the cement loss statistics. The risk of cement loss problem is not sensitive towards flow rate when annulus width and system scale is relative large.

Methods proposed in this report can also help to inform drilling decisions by providing forecasts of zonal isolation risk for particular geological condition.

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