Effect of Perforation Orientations for Sand Prediction

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Effect of Perforation Orientations for Sand Prediction

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The purpose of this research is to study the rock behavior from different perforation orientations**.** The method used in this study is known as the Modified Lade Criterion which applies fully coupled poroelasticity. To investigate the rock behavior, an analytical model, which adopts the Modified Lade Criterion, is used to describe the stress distribution induced by an inclined, cased wellbore using superposition of the inclined cased wellbore system decomposed into the perforation plane. The critical drawdown represents the point at which sand production begins; the algorithm calculates the pressure reduction of a perforation tunnel until rock failure begins. This analytical model allows calculation of critical drawdown pressure to investigate the influence of well completion on sand production. Time-dependence, well inclinations, and perforation direction are also included into the study. This research focuses on four issues: the influence of well completion on the critical drawdown, the time-dependent behavior of the critical drawdown, the preferred perforating direction, and effect of the ratio between maximum and minimum horizontal stresses on the critical drawdown pressure behavior. The simulation indicates that a wellbore perforated in the direction of maximum horizontal stress results in high critical drawdown pressure near the wellbore which declines further in the radial distance. In addition, as time increases, the critical drawdown decreases and converges to the certain value. This research suggests that if sand production is allowed near a wellbore for short time periods, perforating in the direction of minimum horizontal stress in a cased wellbore is preferable to increase critical drawdown for a normal stress regime. However, for more accurate results, applying a 3D poroelastic model is recommended. A developed critical drawdown prediction model is proposed in this research which does not require any MATLAB background. The effect of all parameters on the critical drawdown pressure calculation is determined by sensitivity methods and the most significant parameters are identified. The sensitivity results guide the users before using the default values from the application.

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Chapter 1
Introduction

1.1 Introduction

Sand production is a major cause of the decrease in oil production and degrades production equipment. It could occur from the perforation tunnel when failure begins. To sustain good production performance, accurately predicting sand production is a significant issue in well design. Although several factors influence sand production [1], the most dominant factor is mechanical. The prediction becomes more complicated when using inclined wellbores together with perforation orientations. This research studies the rock behavior after a perforation and suggests the appropriate perforation direction to minimize sand production.

1.2 Previous Studies

Sand production prediction has been extensively studied; Antheunis et al. [2] attempted to simulate perforation collapse by performing numerous experiments to determine perforation stability. Bratli et al. [3] studied the arching phenomenon and compared their expiremental results to elastoplastic theory. Chenevert et al. [4] calculated the critical drawdown to prevent sand production from perforation collapse. Peden et al. [5] determined the factors contributing to and controlling sand production. Seehong et al. [6] predicted the critical drawdown pressure (CDP) in high rate gas wells from an analytical model. However, the effect of well completion on the stress distribution was ignored in most previous works and a fully coupled poroelastic model was not taken into account in. Recently, Hyunil [1] investigated the behavior of critical drawdown based on the fully coupling effect on sand production and the time-dependent behavior of the critical drawdown. His study included only two perforation azimuths, which were at minimum and maximum horizontal stresses. In addition, the ratio of maximum and minimum horizontal stresses was fixed at one value. In this work, we extend study Hyunil's study [1] using his analytical model. However, the details of previous works will be described in background section.

1.3 Purpose of the project

The project develops the sand production prediction model from the approaches of Antheunis, Bratli, Chenevert, Peden, and Hyunil which the objectives are as follows: (1) investigate the influence of well completion on critical drawdown; (2) determine the influence of time-dependent behavior of rock matrix stress and pore pressure on critical drawdown; (3) select the proper perforation direction from different perforation azimuths and inclinations; (4) study the effect of stress ratio on critical drawdown behavior; (5) modify Hyunil's analytical model to a more user friendly version; (6) finally, determine the sensitivities of each parameter on critical drawdown pressure.

1.4 Outline of this project

This research will begin with background from the literature and assumptions used in the analytical model, and an explanation of the application methods.

The results of sand production prediction from different scenarios run with this application will be reported and analyzed. This study proposes the perforation orientation for each case scenario. The model interface created in the current study will be presented and guidelines for use of this user-friendly version are provided. There are 27 changeable parameters shown at the interface and the sensitivity for each parameter is conducted. The sensitivity analysis is carried out to identify which parameters are significant, and to guide users to be aware before using the default values from analytical program.

Chapter 2
Literature Review

2.1 Objectives and values from the previous works

The following describes the objectives from previous studies. Anthenuis et al. [2] simulated perforation collapse with elastic theory. They determined the stress and strain distribution around a perforation tunnel. As a result, they could derive the limiting value of shear strain where perforation failure occurred. Bratli et al. [3] conducted the arching phenomenon from unconsolidated sand. They mainly purposed to study the criteria describing the stability and failure of sand including the effect of flowing fluids. Consequently, they listed the parameters that influenced the critical conditions. Chenevert et al. [4] studied the critical drawdown pressure on a low permeability, and abnormally pressured reservoirs. Their objective was to present that a very limited drawdown can be applied to a well with these conditions to prevent the perforation collapse. Recently, Hyunil [1] studied mechanical behavior of casing, cement, and formation using anylytical and numerical models. Sand production prediction is a part of his dissertation. He proposed to develop an analytical model to estimate the critical drawdown pressure from inclined cased wellbore. The additional objectives are to investigate the influences of well completion, time-dependent behavior of the rock matrix stress and pore pressure on critical drawdown pressure. Finally, proper perforation direction was investigated.

2.2 Developing Sand Production Prediction Models

To generate sand production prediction model, many researchers included elastoplastic model, partially coupled poroelasticity and Mohr-Coulomb failure criterion model, elastoplastics with a linear hardening theorem in their models. Anthenuis et al. [2] performed experiments by loading to the failure on a number of thick-walled cylinders of rock material. They applied several axial and radial loads ratios in order to cover the wide range of possible loading situations. In addition, the perforation tunnel radius was included into the investigation. In other words, the perforation collapse was simulated by external loading of thick-walled cylinders of core material until failure occurs. Then, they calculated stress and strain distribution around the perforations from stress-strain behavior of the brittle material. This calculation is based on poro-elastic theory and applied the failure criterion by using elastic limit and yield function in the form of the relationship between principal stresses. Mohr-Coulomb type criterion defines the onset of plastic deformation. Finally, their approach offered the critical stress and strain distribution in terms of a collapse criterion.

Bratli et al. [3] assumed spherical symmetry to simplify the stress distribution because these stresses depends on principal stresses in the material, the fluid pressure and flow rate, the geometry of the arch, and the stress strain relations in the material. The spherical model was generated as two hemispherical arches. They divided the model into internal and external sections but excluded the axial load. Then, partially coupled poroelasticity and

Mohr-Coulomb failure criterion were applied to the model to calculate the stress distribution. Finally, the results from experiments were compared to the theory. The parameters that significantly impacted the results were listed in their findings.

Chenevert et al. [4] discussed the perforation stability, the abnormally pressured, low and high permeability formations and offered equations to calculate perforation rock stresses. They developed the stability criteria on the perforation area to use in the shear or tensile failure criterion. The following are the list of conditions that affect stress behavior: (1) in-situ stresses and pore fluid pressure before drilling the well. (2) The wellbore condition prior to well completion and perforation. (3) Fluid pressure inside perforation. (4) Pore pressure at perforation surface. Consequently, uniform pore pressure prior to perforating was assumed in their model. They assumed a vertical well under isotopic horizontal in situ stresses, uniform horizontal stress, radial pore fluid flow, low and high permeability, partially coupled poroelasticity and the Mohr-Coulomb failure criterion. This model was claimed to be applied only in the brittle rocks.

Peden et al. [5] studied the optimum completion and production conditions to minimize sand production. They developed the prediction model to predict sand stability in friable formations based on stress distribution around perforation tunnel. Their model evaluated the optimum completion characteristics of shot density and pattern, tunnel length and diameter, and production conditions. According to these conditions, maximum production rate with free sand production was expected. They calculated stress distribution using elastoplastic models and assumed the axial symmetry around perforation hole. Rock was assumed isotropic and homogeneous with the pores completely filled with fluid. In addition, plane strain geometry was presumed. Again, Mohr-Coulomb failure criterion was applied to the model but their elastoplastic model is applicable to ductile rocks. As a result, yield criterion is required for stress strain distribution analysis.

Detournay et al. [12] examined the effects of anisotropic loadings along a long cylindrical cavity using elastoplastic theory, which included yield and failure of rock at the same time. The model captured response of brittle rocks which was a practical problem of a deep cylindrical tunnel. This method was complicated so they improved the previous work and created the design charts to predict the size and shape of the failed rock region.

Morita et al. [14] studied the perforation-tunnel stability based on two different factors on sand production: well pressure and local pressure gradient around the cavity. Their model was simplified by using poroelastoplastic materials. Parameter sensitivity was also studied. Their work used three fundamental steps: (1) re-examination of the factors involved in cavity stability by parameter analysis; (2) a parameter sensitivity study that uses a simple analytical method; and (3) a quantitative study using numerical method. Parameter sensitivity was analyzed with analytical solutions for poroelastic and strain-hardening plastic materials. Their research proposed the solutions of the discrepancy in two conventional cavity criteria: one emphasizing fluid flow force or completion pressure loss and another emphasizing boundary load. They assumed Mohr-Coulomb failure type together with linear work-hardening stress strains into their model. In addition, a linear stress strain relation was assumed from unloading till the stress state exceeded the yield surface.

Cui et al. [8] generated solutions for an inclined wellbore using poroelastoplastic theory with the addition of time dependence to pore fluid boundary conditions in order to simulate realistic field conditions. This analytical model was supplemented with asymptotic solutions for both small and large time analysis. Finally, they examined the effect of an inclined wellbore on stress distribution and stability near wellbore. In other words, their model was developed with pseudo 3D poroelastic model and applied by configuring the initial stress concentrations to estimate the stress distribution around wellbore.

Seehong et al. [6] developed an analytical model to predict sand production and critical drawdown pressure (CDP). The model described the perforation and open-hole cavity stability. The Mohr-Coulomb failure criterion together with non-Darcy flow equation was coupled in the model. In addition, both spherical and cylindrical models were used; the spherical model was applicable for cased and perforated wellbore while cylindrical model was suitable for a horizontal open-hole completion. These tensile failure models were applied to predict the maximum sand free rate in high-rate gas completion.

Tronvoll et al. [15] acquired data from Varg field where produces hydrocarbon from heterogeneous sands containing weak and soft layers, partly homogeneous high-permeable and weak sand bodies. The input data was adopted from leak-off test data, wellbore caliper data, formation strength indicators, productivity index and skin, sand production observation, and reservoir properties. Their method was based on the Kirsh solution for linear elastic stress distribution around a circular opening and vertical wells. Hence, the simulations were governed by 3D poroelasticity theory but did not improve the estimate of horizontal stress anisotropy. They analyzed the sand production risk prior to well completions and proposed the combination of perforation stability computations, selective and oriented perforations in order to minimize the sand production risk.

Zhang et al. [16] determined a technique for generating failure models expected to improve their drilling and completion practices. 3D poroelasticity finite element methods (FEMs) were included in the perforation tunnel stability model. In addition, stress distributions and failure development were generated for different perforations. Finally, they described the parameters that significantly affect the perforation tunnel. In addition to the parameters influence on perforation instability, the relationships between parameters; i.e., critical drawdown pressure, perforation orientation, rock strength, were proposed to identify optimal perforation design for obtaining maximum production rate without sand production.

Hyunil [1] recently studied the model of sand production prediction. He obtained the stress distribution induced by an inclined cased wellbore. His model used the superposition of inclined cased wellbore system and decomposed into several loading conditions with a plane strain condition. The model included the pseudo 3D poroelastic model developed by Cui et al. [8] and evaluated stress distribution around perforation tunnel of an inclined cased wellbore in terms of spatial and temporal variables. However, his model is different from other researches listed above in that fully coupled poroelasticity was used instead of partially coupled poroelastoplasticity. A cylindrical coordinate system, a plane strain condition, and a homogeneous isotropy were assumed in the model. Non-Darcy flow was ignored and only radial flow was considered in his assumption. In addition, the initial pore pressure was presumed to be uniform in the entire reservoir. Finally, critical drawdown pressure before sand production occurred was computed. His work was carried out by using MATLAB to the calculate critical drawdown pressure.

These previous works lacked a few issues related to a complete critical drawdown prediction model. The most significant concern is the fully coupled poroelasticity; all previous works applied partially coupled poroelasticity. This methodology was avoided because it added complexity. However, it does not have the coupling influences between rock matrix stresses and pore pressure [1]. Some models used elastic theory which also simplified the code to analyze stress strain distribution in their models. In addition, 3D poroelasticity theory has not been applied into the previous works because of the complexity. 2D was used instead and the results slightly distorted from actual situations in the subsurface.

In summary, most of previous works on perforation tunnel stability ignored the effect of well completion on the stress distribution or maintained some distance from wellbore to avoid the influence well completion [1]. Besides fully coupled poroelastic theory, time-dependent behavior was not considered in previous works.

Nevertheless, Hyunil's [1] research applied the 3D fully coupled poroelastoplastic in order to analyze effect of coupling on sand production predicted. The time-dependent behavior of the critical drawdown was included as one parameter in his study. Unfortunately, the effect of perforation orientation on critical drawdown pressure was determined at only two directions which were at the direction of minimum and maximum horizontal stresses. Other perforation azimuths and perforation inclination have not yet been studied. Though his application is greatly useful to design the optimal perforation design in order for sand production free, it is required users to understand MATLAB. More importantly, the study of effect from each parameter on critical drawdown prediction is significant. This issue should be included in the study of sand production prediction model. As a result, the users must be careful when they use the default value from the analytical model.

Chapter 3
Methodology and Assumptions

3.1 Sand Production

This section discusses the methods for calculating the stress distribution around a perforation of an inclined cased wellbore, and for applying proper failure criteria for sand production prediction. This method involves three steps: obtain the stress distribution around an inclined cased wellbore caused by drilling and well completion; achieve the stress distribution around a perforation in that particular wellbore; and apply an appropriate failure criterion to the assumption and predict sand production. The first two steps are elaborated in the next section while the last step is described in sand production prediction application.

3.1.1 Stress distribution around the perforation of an inclined cased wellbore

The perforation is required to create communication between the reservoir and the wellbore. However, perforations generate holes which induce a stress disturbance to the system. The initial stress state is the stress distribution around the inclined cased wellbore. To reduce the complexity of the solution, a plane strain condition is used instead of a generalized plane strain. Then, the final induced stresses are estimated from second order tensor summation of the initial stress and the disturbed stress as shown below [1]:

$$\sigma_{induced} = \sigma_{initial} + \Delta\sigma_{disturbed}$$

This analysis distinguishes between partially and fully coupled poroelasticity. Partial coupling between pore pressure (fluid) and rock matrix stress (solid) allows only one influence, which is the effect of pore pressure on matrix stress. It excludes the effect of rock matrix stress on pore pressure. Full coupling considers both influences simultaneously. This research uses analytical models which include the fully coupled poroelasticity to calculate the stress induced by a perforation ([7] – [10]). In order to consider an inclined open wellbore system under in situ stresses and wellbore pressure with fully coupled poroelasticity, Cui et al. ([7] – [10]) deconstructed loading conditions into three different problems: a poroelastic plane strain problem, an elastic uni-axial stress problem, and an elastic anti-plane (off-plane) shear problem. However, only the poroelastic plane strain problem was divided into three more problems: a far-field isotropic stress problem (Lame problem), a virgin pore pressure problem, and a far-field deviatoric stress problem.

3.1.2 Sand production prediction application

This section describes the assumptions and methods which apply the appropriate failure criterion to predict sand production. The assumptions and methods are from the Hyunil's [1] study.

3.1.2.1 Assumptions for sand production prediction

Sand production prediction requires the following assumptions:

1. A perforation tunnel is assumed to be cylindrical; therefore, a cylindrical coordinate system must be used.

2. Two angles are needed in order to identify perforation orientation: an angle from wellbore (perforation inclination) and an azimuth angle in the plane perpendicular to wellbore (perforation azimuth).
3. A plane strain conditions are assumed on the plane perpendicular to the perforation tunnel.
4. The radius of the perforation tunnel is ignored because it is assumed to be very small compared to the wellbore radius [11]. Hence, the initial stresses caused by an inclined cased wellbore are considered to be uniform on a cross-section perpendicular to the perforation tunnel [1]. If stress gradients or pore pressure gradients are relatively small, this consideration is acceptable.
5. The permeability tensor is assumed as homogeneous isotropic [1].
6. This research ignores the non-Darcy effect although a well with a high velocity gas flow must consider the non-Darcy effect due to a turbulent Reynolds number.
7. Fluid is assumed to flow in the radial direction, which is the dominant flow during production.
8. Fluid is slightly compressible or incompressible; otherwise, high compressibility will generate more complicated problems.
9. Initial pore pressure is assumed to be isotropic in the entire reservoir before perforation, which is reasonable. Pore pressure has enough time to stabilize from the reservoir to wellbore before perforation.

10. Pressure in the perforation tunnel is assumed to be similar to the wellbore pressure.

3.1.2.2 Methodologies for sand production prediction

The steps to calculate the stress distribution around a perforation tunnel are follows. Figure 3.1 depicts the coordinate systems in both the wellbore and the perforation tunnel. First, we apply two orientation angles of a perforation tunnel from borehole coordinate to perforation tunnel coordinate to alter the coordination of initial stresses induced by an inclined cased wellbore. Mathematically, second order tensor matrices are used in this section as follows: a) Estimate the stresses induced by the inclined cased wellbore with borehole coordinates at the given perforation orientation information; b) Adjust the new initial stresses with a cylindrical coordinate system back into the borehole Cartesian coordinate system; c) Rotate the coordinate system using the azimuth angle of the perforation tunnel about the wellbore axis; and d.) Again, rotate from the wellbore axis the coordinate system with the perforation inclination.

Second, we apply the derivation from Cui et al.'s work ([7]-[10]) to calculate the stresses around a perforation tunnel. Finally, we superimpose the new initial stresses from an inclined cased wellbore and at a perforation tunnel [1]. Then, the stress distribution is obtained as functions of plane coordinates of the perforation coordinate (R, ϕ) and time.

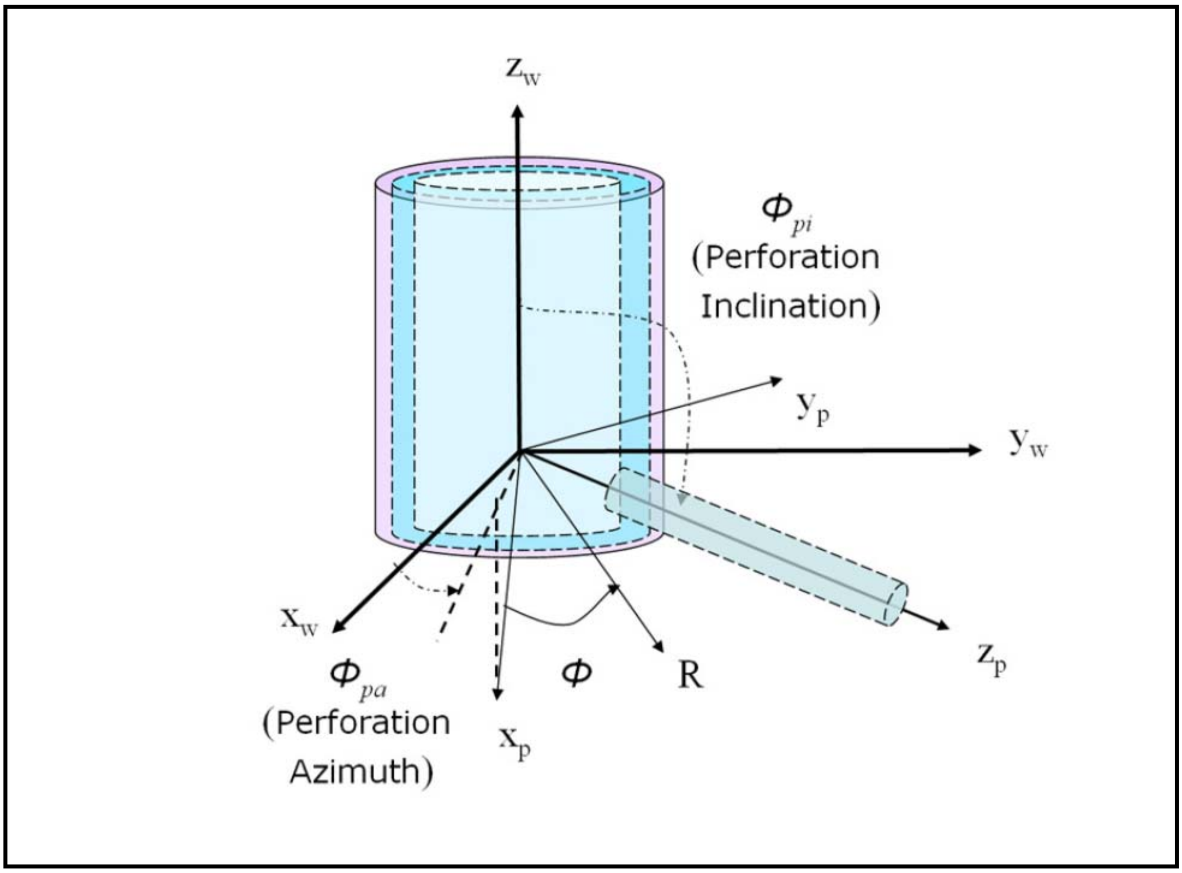

Figure 3.1: Wellbore and Perforation Coordinate System [1]

3.1.3 Critical Drawdown Pressure Calculation

If the proper yield criteria, failure criteria, and assumptions of rock material are applied, it is possible to predict and estimate the rock failure around the perforation tunnel, and critical drawdown can be obtained.

3.1.3.1 Assumptions for critical drawdown pressure prediction

Generally, rocks are categorized as soft rock (ductile) and hard rock (brittle). There is a small difference between the yield point and failure point of brittle rock while ductile rock shows a relatively larger difference. Therefore, yield criteria are not necessary for brittle rock but failure criteria are. For ductile rock, both yield and failure criteria are required at the same time; several elastoplastic models were developed for ductile rock. Unfortunately, these models involve complicated mathematics, even for the simple cases. This research will not use the elastoplastic model, but will assume brittle rock with the proper failure criteria. Each failure criterion has unique conditions under which the criterion was developed [1]. For example, the Mohr-Coulomb failure criterion assumes that there is no impact on rock strength as a result of intermediate principal stress. This simple criterion is often used. However, other failure criteria were developed and included the effect of the intermediate principal stress on rock strength. The Drucker-Prager and Modified Lade failure criteria also include the intermediate principal stress but the former failure criterion emphasizes the intermediate principal stress as much as it does the major and minor principal. Therefore, this research adopts the Modified Lade criterion for failure criteria.

3.1.3.2 Methodology for critical drawdown pressure prediction

An algorithm whereby a perforation tunnel pressure is reduced gradually until rock failure begins is used to predict the critical drawdown when sand production occurs. The pressure at the perforation tunnel is assumed to be identical to the wellbore pressure and its maximum pressure is at the initial state. In addition, the reservoir is assumed to have an infinite boundary; the initial pore pressure is taken as the representative reservoir pressure [1]. MATLAB is used in this research to simulate all processes. Several factors affect the critical drawdown pressure or rock strength; this research does not only calculate the critical drawdown, it also provides guidelines for the design of the perforation orientation. Three major issues influence the critical drawdown pressure calculation: the influence of well completion, time-dependence, and the preferred perforation direction.

3.2 Critical drawdown study

3.2.1 Assumptions for critical drawdown study

As described earlier, this research extends the Hyunil [1] study, the results from the parameters in his findings are assumed to be the Base Case. The critical drawdown section in Hyunil's [1] research covered only the results from the perforation direction of maximum (0° perforation azimuth) and minimum (90° perforation azimuth) horizontal stresses. Hence, the input data in the Base Case is modified based on the previous studies [1] by adding more perforation azimuth from only 0 and 90 degrees to be 0, 30, 36, 45, 60, 90 degrees. Each parameter from the input is determined on a case by case basis and the results from these parameter sensitivities will be analyzed.

3.2.2 Methodologies for critical drawdown study

The results of the sensitivities from each parameter are analyzed and compared to the Base Case. These results will indicate the preferred perforation for each case. Note that time-dependence is also included by increasing time from 0.001 to 500 days and using the same reservoir properties for each case. The model takes spatial behavior on the critical drawdown pressure analysis by adjusting the radial distance from wellbore (r/R_3) by 1, 1.1, 1.2, 1.5, 2, 3, 5, 10. The following is a list of cases studied in this research.

1. Base Case: well inclination and azimuth are 0° while perforation inclination is 90°. The perforation azimuth varies from 0° to 90°. Maximum and minimum horizontal stresses are 0.9 and 0.7 psi/ft, respectively. Initial pore pressure is 0.45 psi/ft.
2. Case 2 differs from the Base Case by varying the perforation inclinations from 30° to 90° using regular increments.
3. Case 3 deviates from the Base Case by modifying the well inclination from 0° to 10° and leaving everything else at the original input.
4. Case 4 has isotropic horizontal stresses or has identical maximum and minimum horizontal stresses.
5. Case 5 measures whether the preferred perforation direction would remain the same as the Base Case when the ratio between maximum and minimum horizontal stresses is modified from 1.286 to 1.2.
6. Case 6, 7, 8, 9, 10 are similar to case 5 but their ratios between maximum and minimum horizontal stresses are 1.4, 1.6, 1.8, 2.0, 3.0, respectively.
7. Finally, the sensitivities of all 27 parameters are determined in order to test which parameters significantly impact the critical drawdown pressure.

3.3 Critical Drawdown Program Tutorial

This research used the analytical model presented in Hyunil's [1] study. The model is used with MATLAB and requires users to manually adjust parameters for each case. In addition to determining the critical drawdown pressure behavior, this research also provides a user-friendly version of a critical drawdown prediction model that requires no MATLAB knowledge. The tool developed consists of 27 different parameters which allow us to vary the data by putting a comma between two data entries. For example, in the case of time after perforation, data must range from 0.001 to 500 with different increments. The interface of MATLAB model allows users to type 0.001, 0.01, 1, 10, 100, 500 in the box beside time after the perforation input. However, if users do not know how to fill in the data, this program provides an open button for users to pull out the default input and users are likely to adjust the data from those particular data. Once the data is ready, the run button is clicked and the program will immediately simulate the critical drawdown pressure data for each case. The results of the simulation are shown on the next page. This model interface has the capacity to plot the results with different parameters: r/R_3, perforation azimuth, perforation inclination, time after perforation, etc. The plot allows for both two and three dimensions. Finally, output can be captured and saved as a MATLAB file for future use.

Chapter 4
Results and Discussion

4.1 Results of the cases studied

This section shows the results of the 10 cases studied and the parameter sensitivity research using the analytical critical drawdown calculation tool modified from Hyunil's [1] application. These 10 case scenarios focus on four issues: the influence of well completion on the critical drawdown, the effect of the ratio between maximum and minimum horizontal stresses, preferred perforation orientation, the time-dependent and spatial behavior of the critical drawdown. The following sections describe input data into the analytical model and the results for each case scenario.

4.1.1 Base Case

Table 4.1 shows input data for the Base Case was run in Hyunil's [1] study. His objective was to determine the preferred perforating direction, and the influence of time-dependent and spatial behavior on sand production prediction. A number of time-dependent after perforation, radial wellbore distances were varied while the other parameters were kept constant. The perforation azimuths were initially fixed at maximum (0°, σ_H) and minimum (90°, σ_h) horizontal stresses directions. Additional perforation azimuths were added into the Base Case in this study to determine the preferred perforation orientation from all possible perforating directions. Results of the Base Case are shown in Figure 4.1 which plots the critical drawdown pressure and perforation azimuth. Several plots of the relative radial distance from the perforation tunnel center (r/R3) represent the spatial pattern of the critical drawdown at time 0.001 day after perforation. Critical drawdown pressure ranges between 1940 – 2080 psi. This figure indicates that critical drawdown pressure tends to increase the closer the perforating direction is to the minimum horizontal stress for anywhere further from wellbore; however, the opposite trend occurs near wellbore. The critical drawdown pressure trend becomes clearer as time after perforation increases, as shown in Figure 4.2, except that the critical drawdown pressure is in the range of 1700 – 2000 psi. This behavior implies that if some sand production near the wellbore is acceptable, perforation in the direction of σ_h decreases sand production.

Input	***In-situ principal stresses, and initial pore pressure***			***Additional Data***		
	Reservoir			***Material Properties***		
	Po (Initial Pore Pressure)	0.45	psi/ft	SH (Max Horiz Stress)	0.9	psi/ft
				SHh (Ratio Max/Min Horiz Stress)	1.286	psi/ft
	Time after perforation			Sv (Vertical Stress)	0.7	psi/ft
	time	0.001,0.01,1,10,100,500	days	Casing Young Modulus (E1)	3.E+07	psi
				Cement Young Modulus (E2)	3.E+06	psi
	Wellbore Orientation			Rock Young Modulus (E3)	2.E+06	psi
	Azimuth	0	deg	Casing Poisson Ratio (nu1)	0.3	
	Inclination	0	deg	Cement Poisson Ratio (nu2)	0.25	
				Undrainned Poisson Ratio (nu3)	0.219	
	Perforation Orientation			Rock Poission Ratio (nuu)	0.461	
	Perforation Depth	5000	ft			
	Azimuth	0,90	deg	**Coefficients**		
	Inclination	90	deg	Skempton coefficient (B)	0.915	
				Biot-Willis coefficient (Alpha)	0.968	
	Geometry of Casing, Cement, Rock			Poroelastic stress coefficient (eta)	0.348	
	r/R3 (R3 = Rock)	1,1.1,1.2,1.5,2,3,5,10		Consolidation coefficient / hydraulic diffusivity (C)	23.97	in^2/day
	R1 (Casing, IR)	2.5	inch	Mohr-Coulomb friction angle (phi)	35	deg
	R2 (Cement, IR)	2.8	inch	UCS Rock strength	3500	psi
	R3 (Rock, IR)	3.2	inch			

Table 4.1: Base Case Input Data for Sand Production Prediction Model

Time-dependent behavior is shown in Figure 4.3, which plots the critical drawdown pressure and the time after perforation at the wellbore for all perforation azimuths. At the wellbore, critical drawdown pressure is stable after 0.01 day of perforation. In addition, all perforation azimuths show similar trends with almost the same critical drawdown pressure. In contrast, the critical drawdown pressure trend becomes clearer when moving further from the wellbore, as shown in Figure 4.4. The graph proves that after 0.01 day of perforation, time does not influence the critical drawdown pressure. However, this plot confirms that perforating at the direction of σ_h is more effective and that the pressure seems to decrease when moving closer to the direction of σ_H.

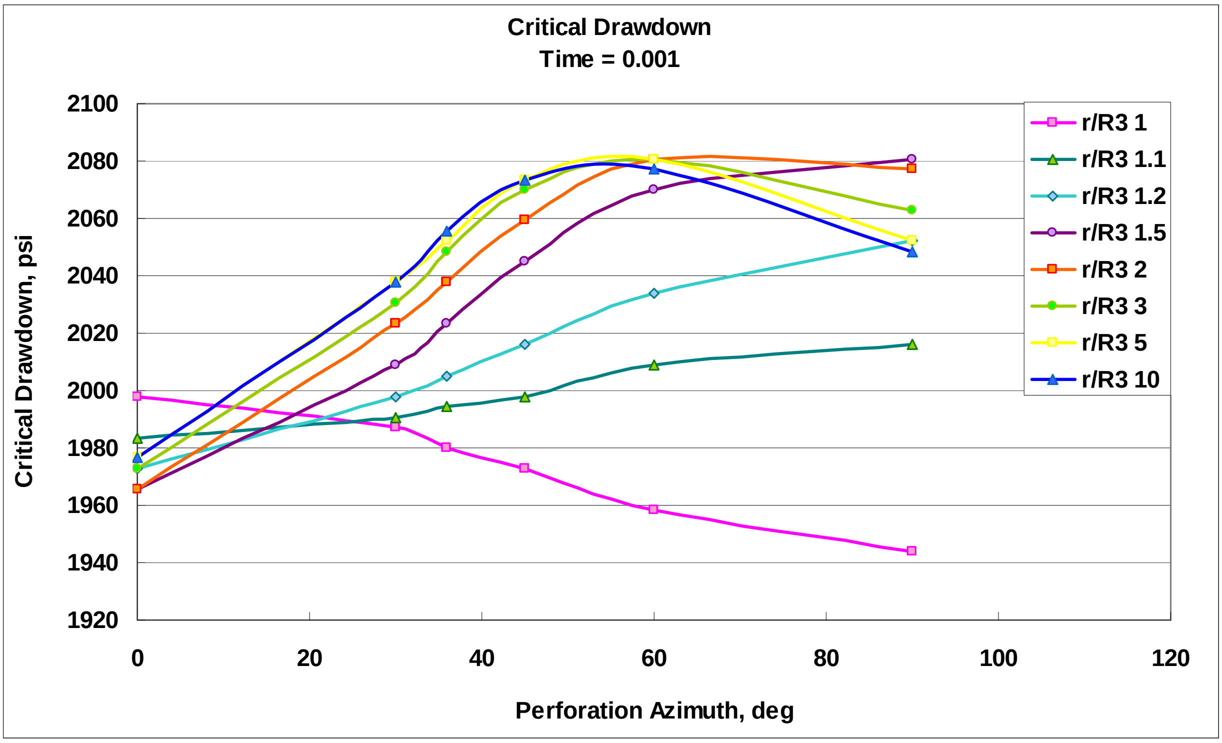

Figure 4.1: Base Case critical drawdown pressure versus perforation azimuth for t = 0.001 day

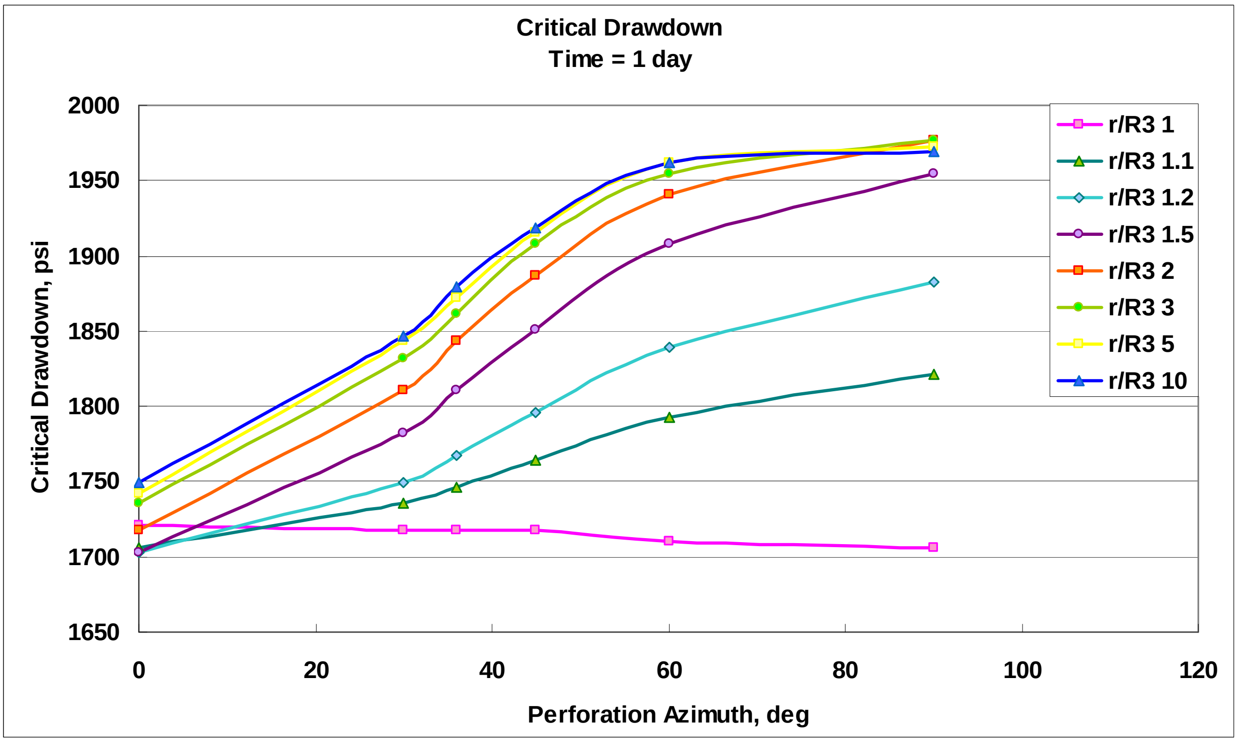

Figure 4.2: Base Case critical drawdown pressure vs perforation azimuth for t = 1 day

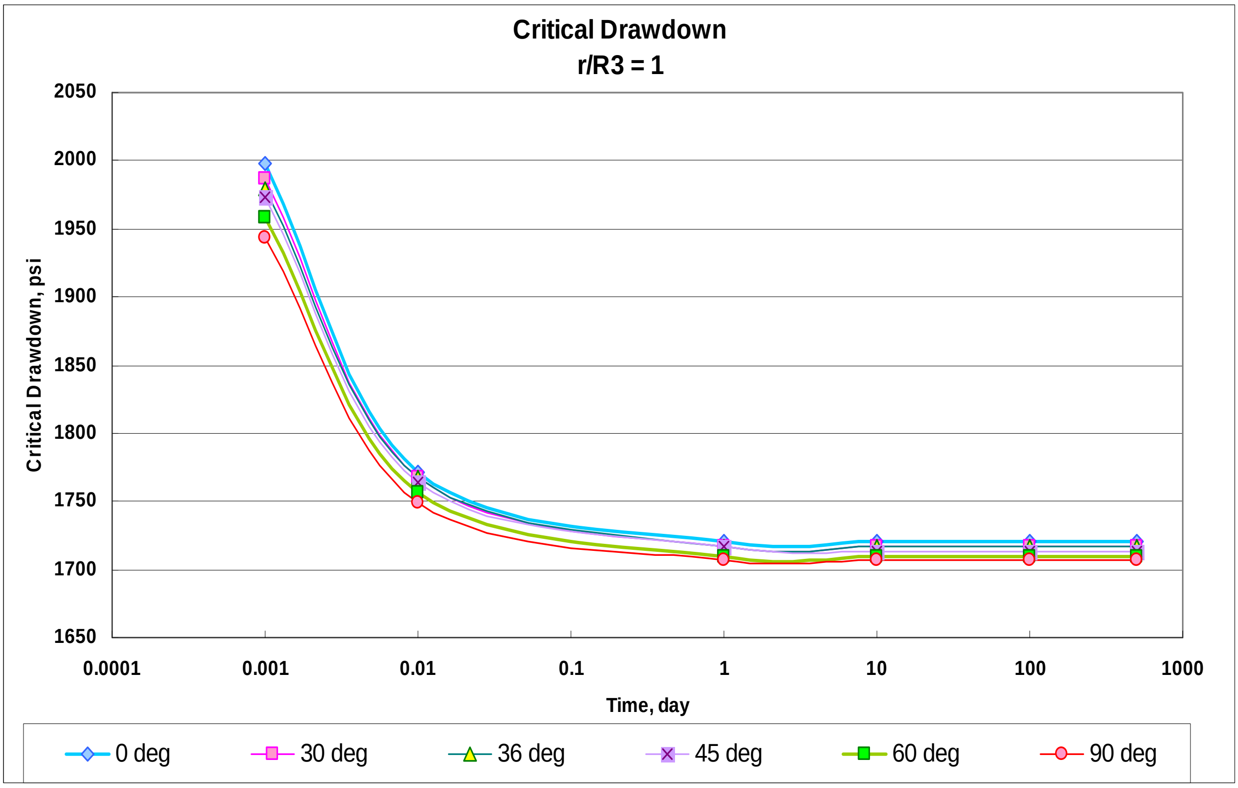

Figure 4.3: Base Case critical drawdown pressure vs time after perforation for r/R3 = 1

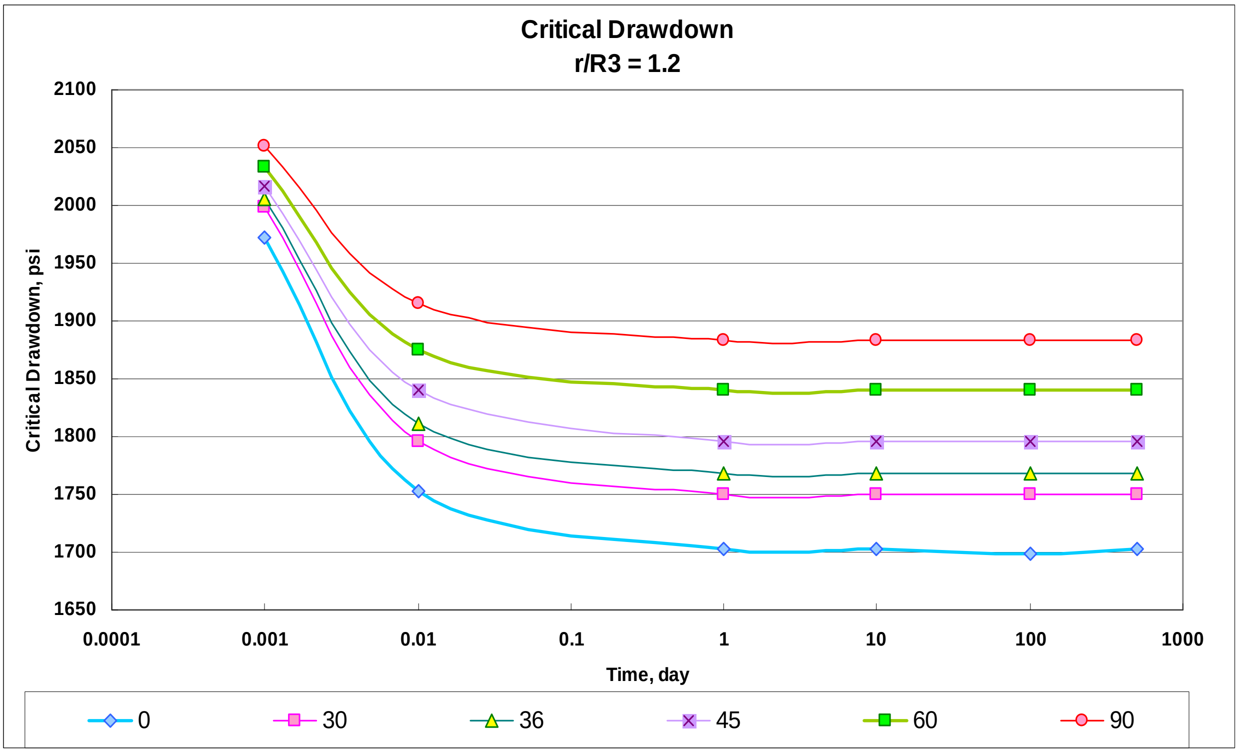

Figure 4.4: Base Case critical drawdown pressure versus time after perforation fort r/R3 = 1.2

4.1.2 The effect of perforation inclination on critical drawdown pressure, Case 2.

Case 2 uses input data similar in the Base Case, but the perforation inclination was altered from 90 to 30, 45, 60 degrees. The perforation azimuths are fixed at 0° and 90°. This case studies the sand production prediction behavior from different perforation inclinations. The results in Figure 4.5 show the influence of perforation inclination on critical drawdown pressure behavior at a perforation azimuth of 0°. The critical drawdown pressure ranges from 1450 to 2000 psi.

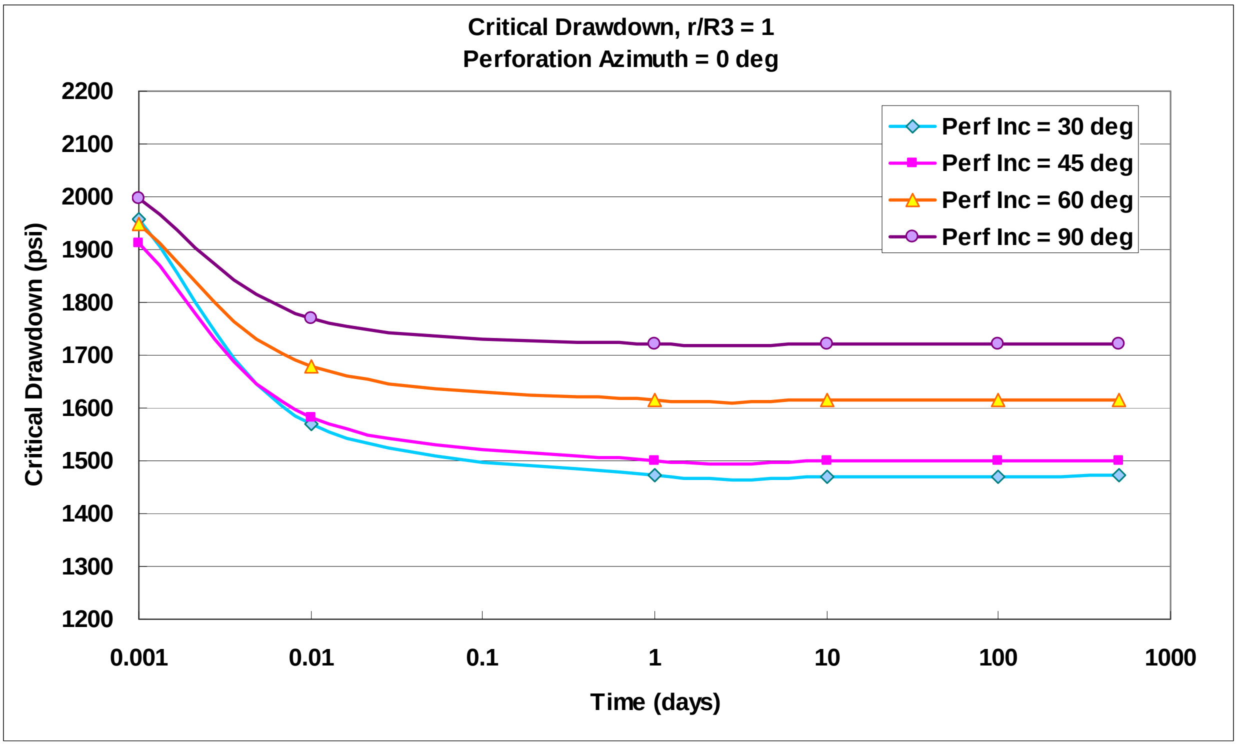

Figure 4.5: Case 2 critical drawdown pressure vs time after perforation for r/R3 = 1, Perforation azimuth = 0°

It can be seen in Figure 4.5 that the perforation inclination of 90° results in the maximum critical drawdown pressure when perforation is in the direction of maximum horizontal stress (90°) at the wellbore. The perforation inclination of 30 and 45 degrees tends to produce almost the same sand production rate and the lowest critical drawdown pressure occurs at these two levels of perforation inclination. Similarly, the shape of the critical drawdown pressure for the perforation azimuth of 90° at the wellbore (Figure 4.6) is close to the trend in Figure 4.5 but it looks clearer in the difference of the critical drawdown pressure values between the perforation inclination of 30 and 45 degrees. In Figure 4.6, critical drawdown pressure is within a range of 700 – 2000 psi

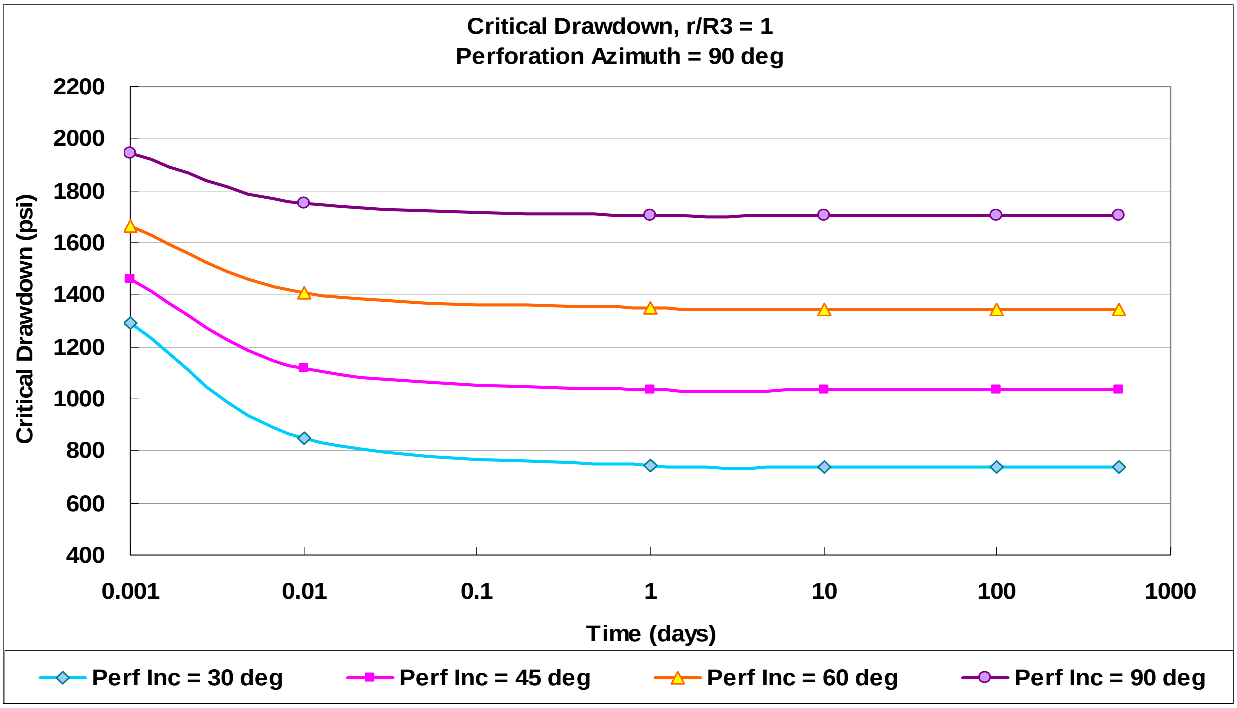

Figure 4.6: Case 2 critical drawdown pressure vs time after perforation for r/R3 = 1, Perforation azimuth = 90°

In contrast, a perforation inclination of 90° is not the preferred perforating direction when moving further from the wellbore for both 0° and 90° perforation azimuths as shown in Figure 4.7 and 4.8. Instead, a 30° perforation inclination and 0° perforation azimuth provides the lowest sand production risk when moving further from the wellbore. A perforation inclination at 45° is preferred if perforating with 90° of perforation azimuth. However, a comparison of the two figures – Figure 4.7 and 4.8, perforating in the direction of minimum horizontal stress produces the highest critical drawdown pressure.

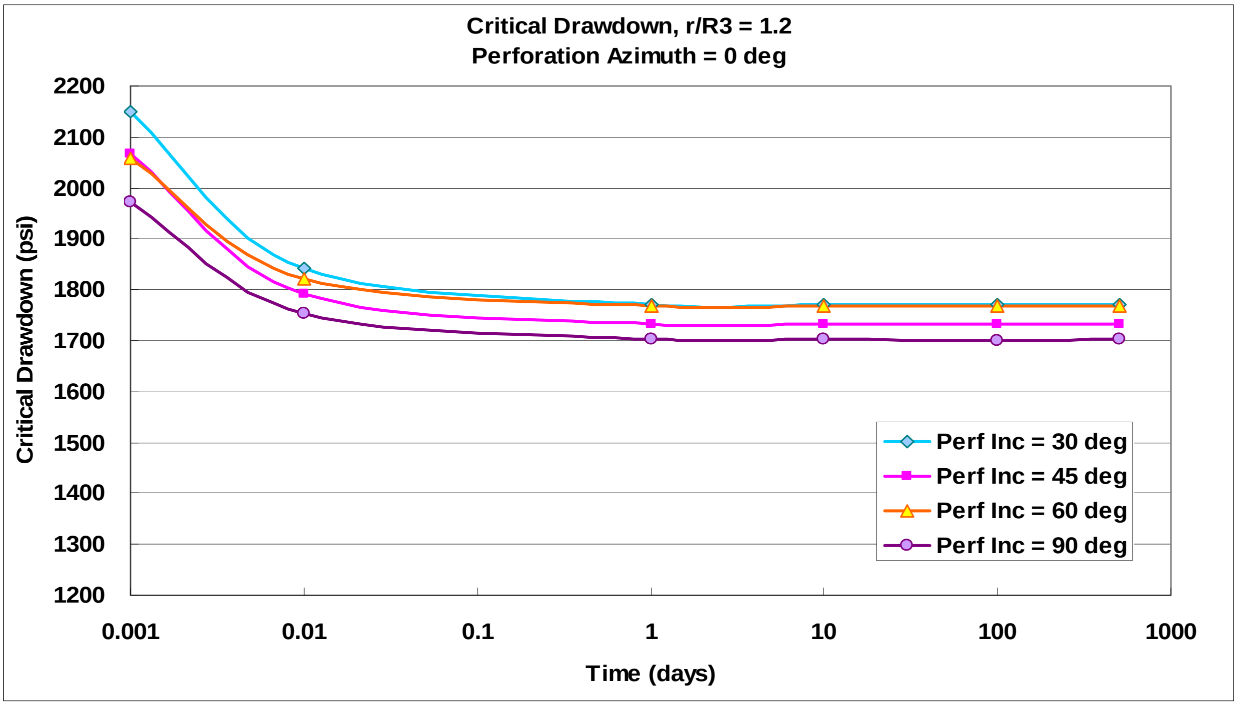

Figure 4.7: Case 2 critical drawdown pressure vs time after perforation for r/R3 = 1.2, Perforation azimuth = 0°

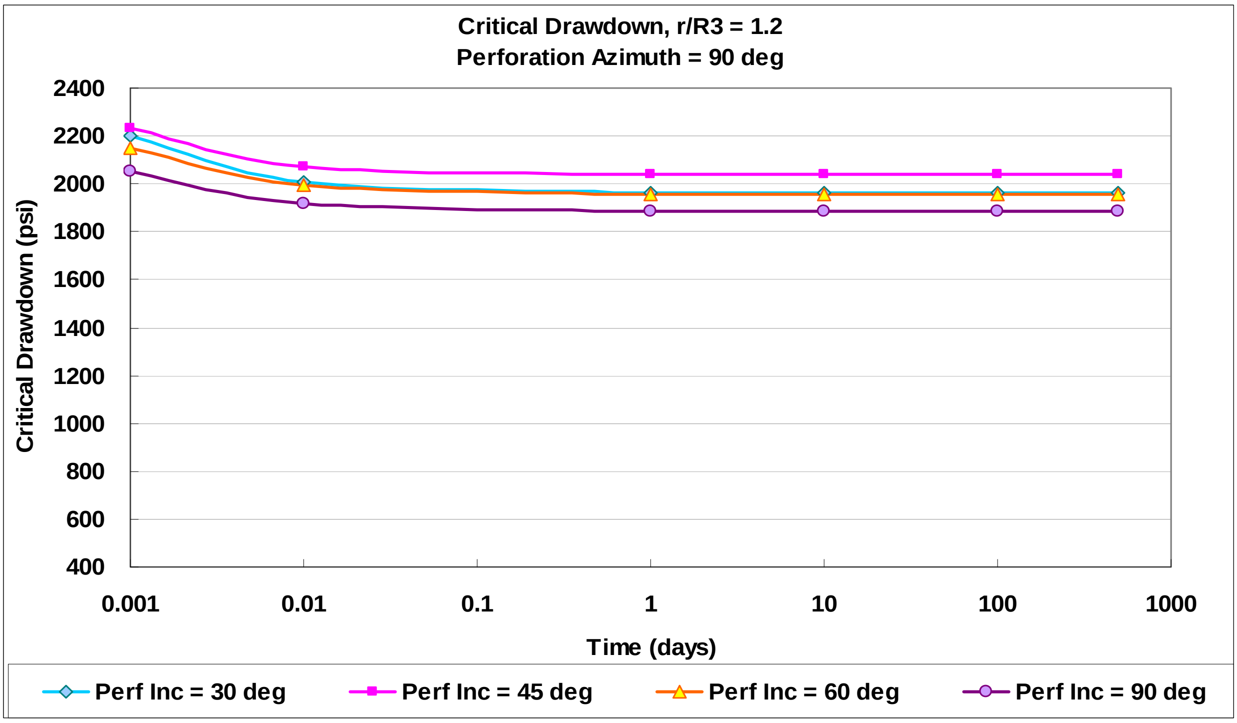

Figure 4.8: Case 2 critical drawdown pressure vs time after perforation at r/R3 = 1.2, Perforation azimuth = 90°

Figure 4.7 and 4.8 indicates that the overall critical drawdown pressure will be higher at the distance further from the wellbore but the trends in both figures are similar to the plots from the distance at wellbore.

4.1.3 The effect of well inclination on critical drawdown pressure, Case 3.

This case differs from the Base Case in that the wellbore inclination was adjusted from 0° to 10°. Case 3 studies the influence of wellbore inclination on critical drawdown pressure. Figure 4.9 shows the critical drawdown pressure with perforation azimuths at a variety of relative radial distances (r/R_3). The results for this case are similar to the Base Case in that the perforation in the direction of 90° is preferred for all relative radial distances except at wellbore. Consequently, the pressure trend is clear when time after perforation increases to 1 day, and 90° of perforation azimuth is selected. However, critical drawdown pressure from Case 3 is slightly lower than that of the Base Case and is confirmed in Figure 4.11 and 4.12. Besides the decrease in pressure, these figures also agree that 90° of perforation azimuth is preferred.

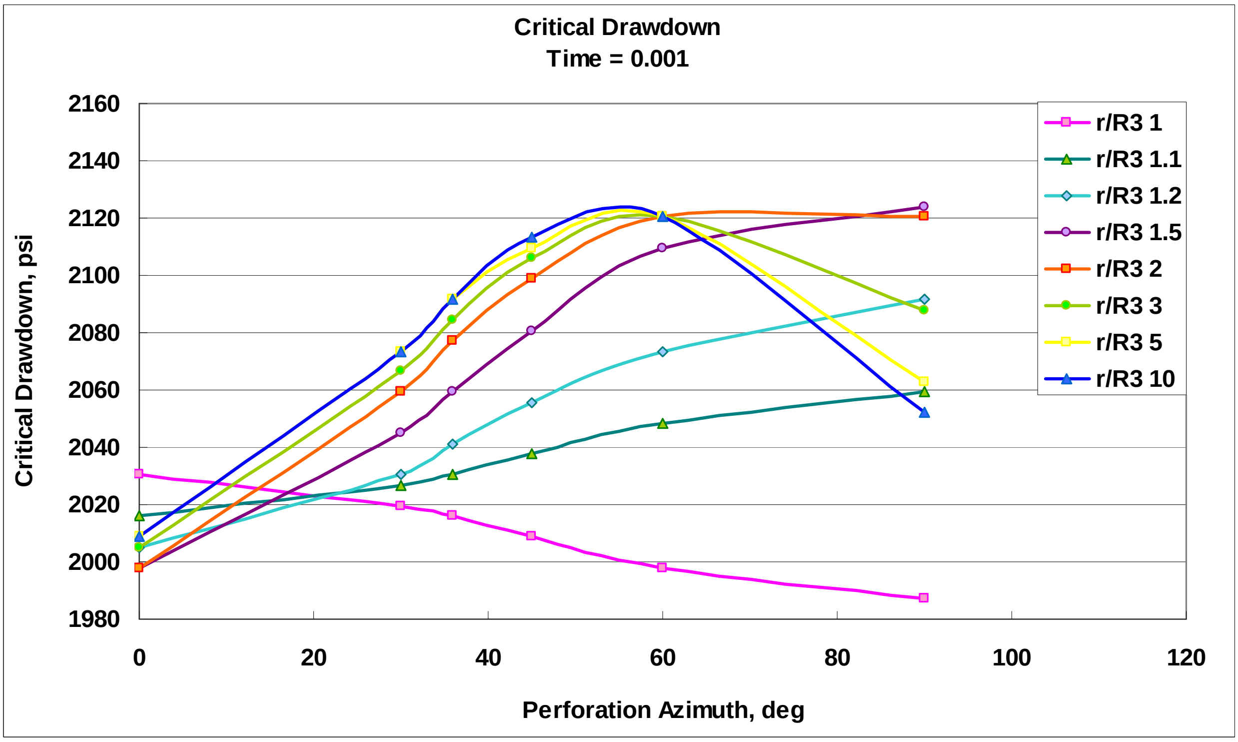

Figure 4.9: Case 3 critical drawdown pressure versus perforation azimuth for t = 0.001 day

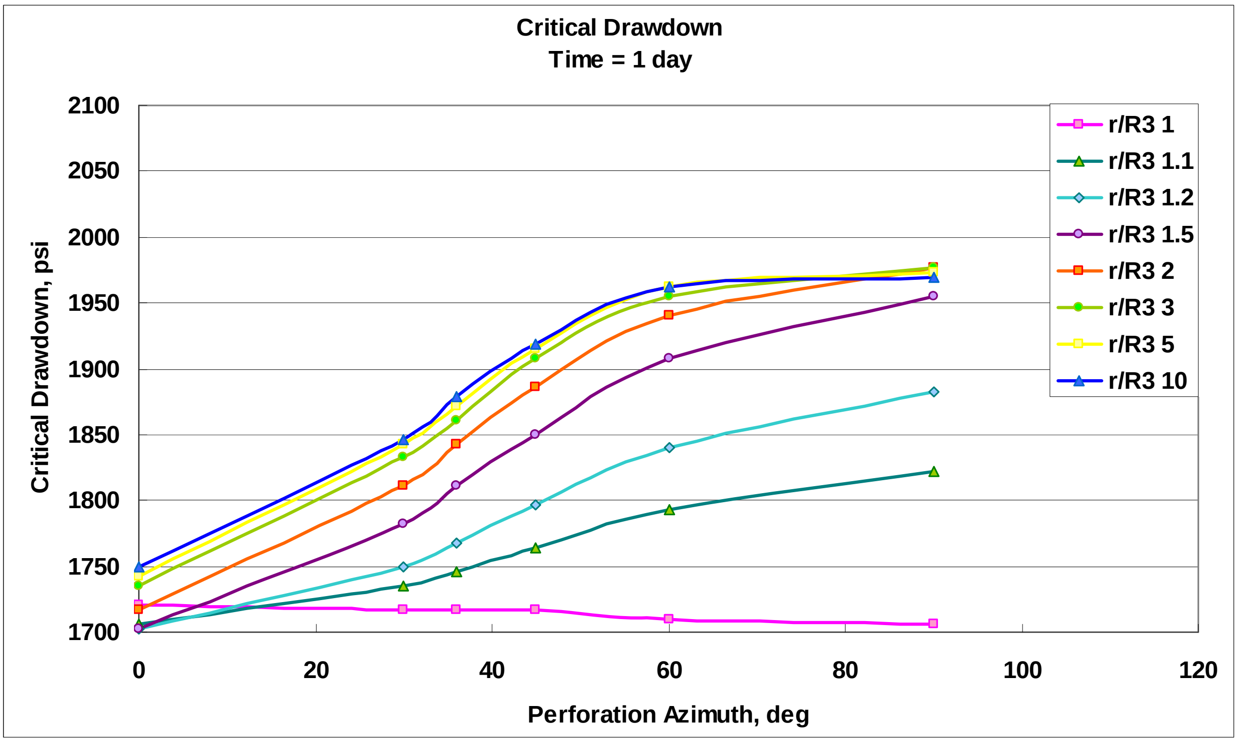

Figure 4.10: Case 3 critical drawdown pressure versus perforation azimuth for t = 1 day

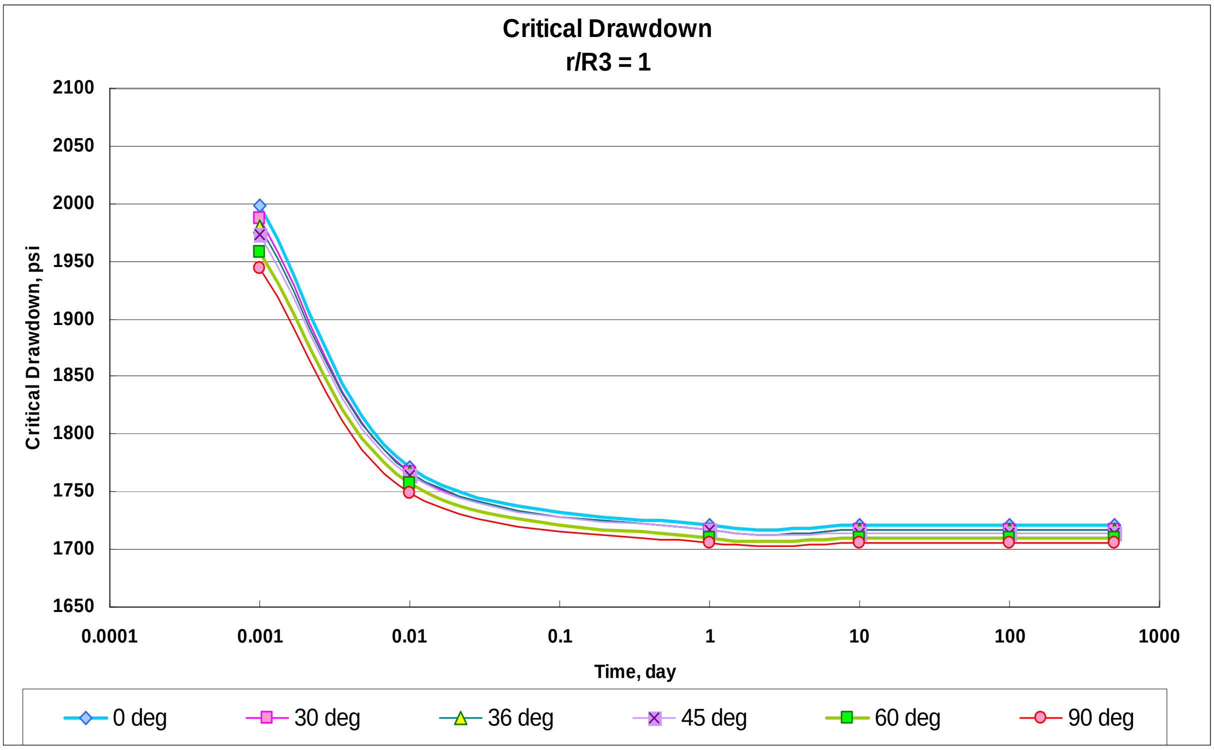

Figure 4.11: Case 3 critical drawdown pressure versus time after perforation for r/R3 = 1

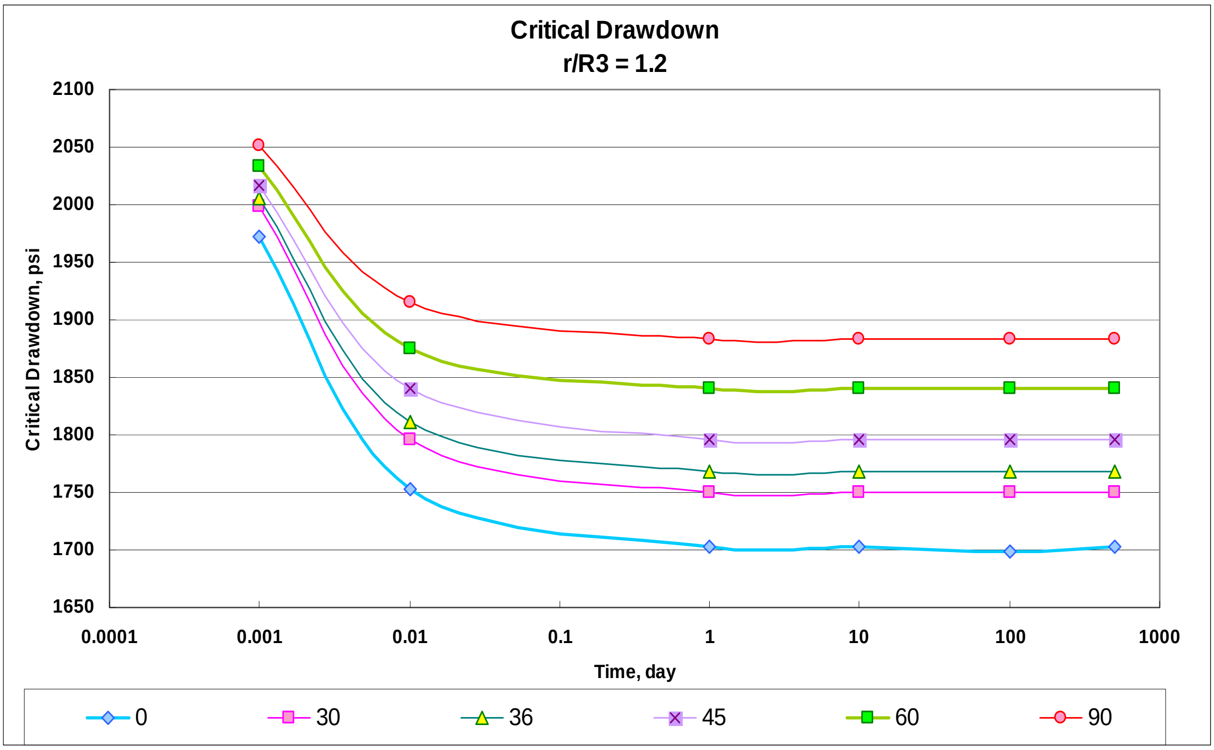

Figure 4.12: Case 3 critical drawdown pressure versus time after perforation for r/R3 = 1.2

4.1.4 The effect of the maximum and minimum horizontal stress ratio

This part contains 7 cases in which the ratio between maximum and minimum horizontal stresses are adjusted and compared to the Base Case. The purpose is to determine the impact of maximum and minimum horizontal stresses on sand production prediction.

4.1.4.1 Case 4 – the ratio of 1

This scenario simulates isotropic horizontal stresses and uses other parameters similar to the Base Case. However, the maximum and minimum horizontal stresses in Case 4 are 0.7 psi/ft while for the Base Case these are 0.9 psi/ft for maximum horizontal stress and 0.7 psi/ft for minimum horizontal stress. Figure 4.13 shows the critical drawdown pressure behavior with time after perforation. A comparison between the Base Case and Case 4 is conducted and both perforation azimuths result in identical critical drawdowns because of the isotropic horizontal stresses. The graph in Figure 4.13 occurs at the wellbore while that in Figure 4.14 shows the results further from the wellbore. These plots present trends similar to the Base Case but their critical drawdown pressures are less than those of the Base Case because of the lower maximum horizontal stress. However, if the well is completed in a zone with isotropic horizontal stress, time after perforation will not influence the critical drawdown behavior and all perforation azimuths will show identical critical drawdown pressure trends.

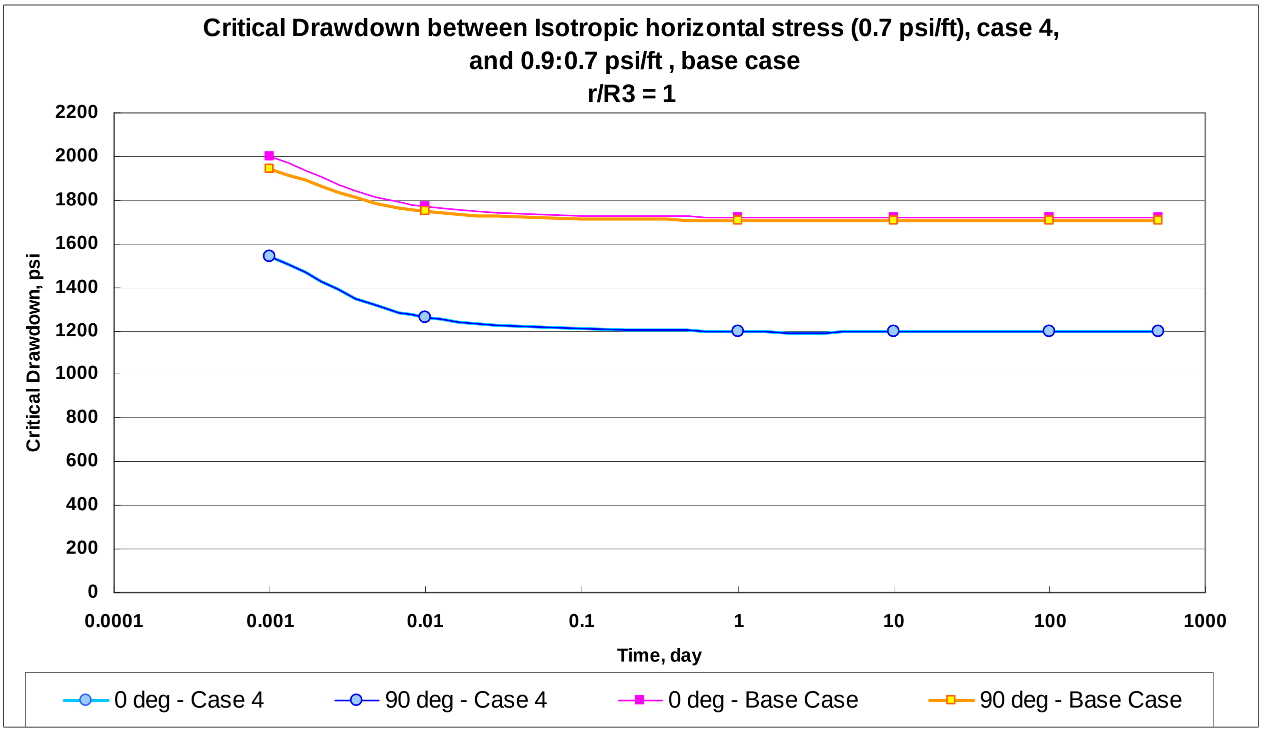

Figure 4.13: Case 4 critical drawdown pressure vs time after perforation for r/R3 = 1

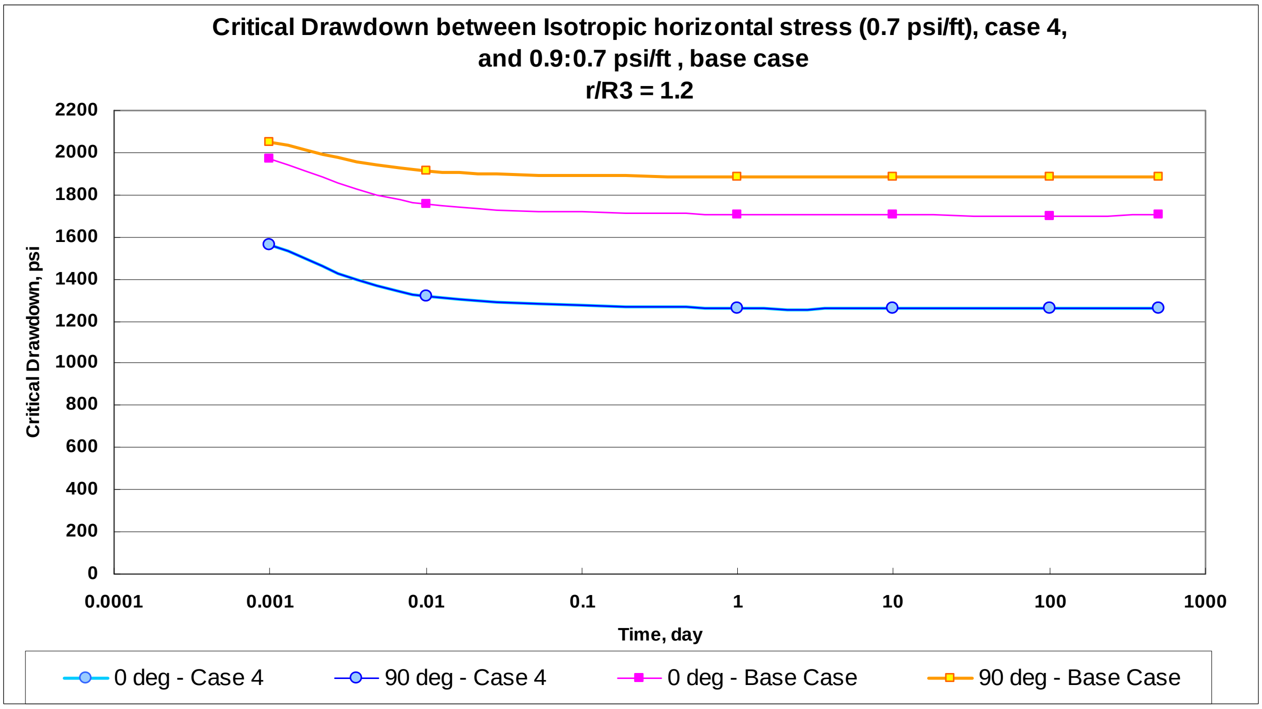

Figure 4.14: Case 4 critical drawdown pressure vs time after perforation for r/R3 = 1.2

4.1.4.2 Case 5 – the ratio of 1.2

This case contains only one parameter different from the Base Case; the ratio between maximum and minimum horizontal stresses is 1.2. The critical drawdown pressure plotted with the perforation azimuth is shown in Figure 4.15 which represents the data 0.001 day after perforation. The pressure is in the range between 2050 and 2200 psi which is higher than the overall trend for the Base Case. However, the trend is similar to the Base Case; perforation in the direction of σ_h is preferred because most radial distances tend to have the maximum critical drawdown pressure in this direction. Figure 4.16 illustrates the same material at 1 day after perforation. The overall curve is within the range of 1850 – 2100 psi, which is lower than in the earlier period but the perforation direction is still the same as confirmed by Figure 4.18.

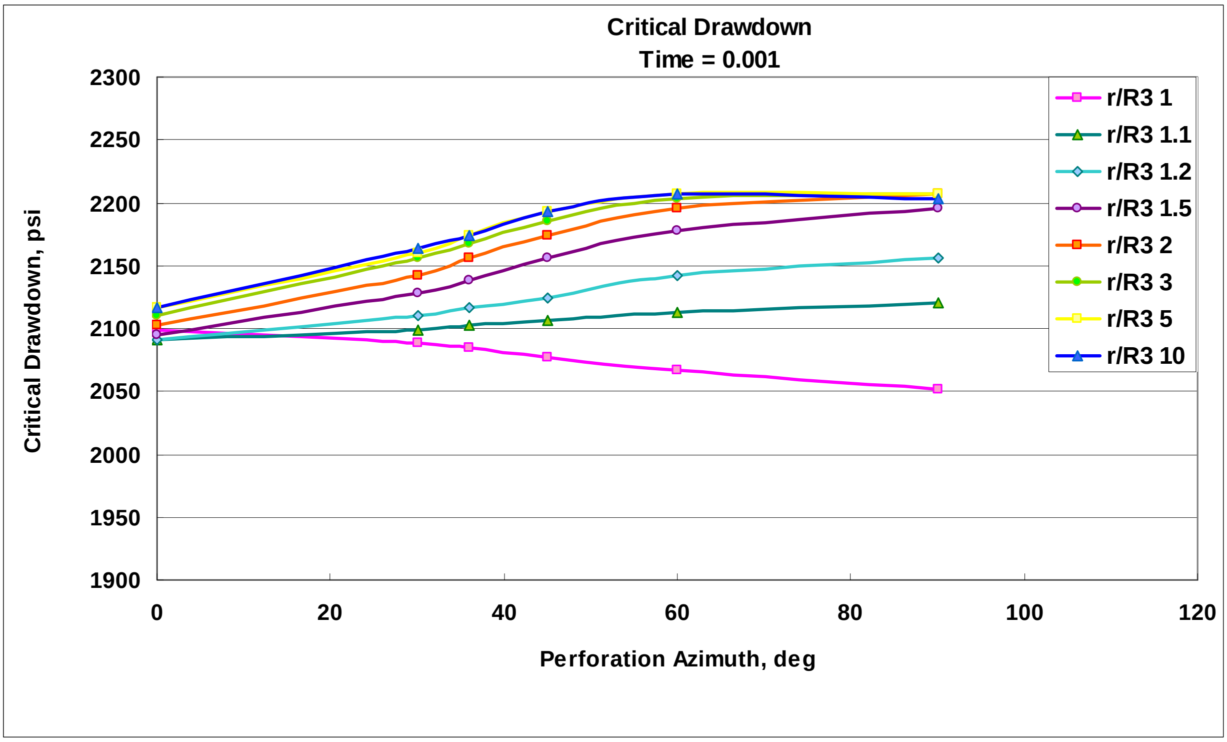

Figure 4.15: Case 5 critical drawdown pressure versus perforation azimuth for t = 0.001 day, ratio of 1.2

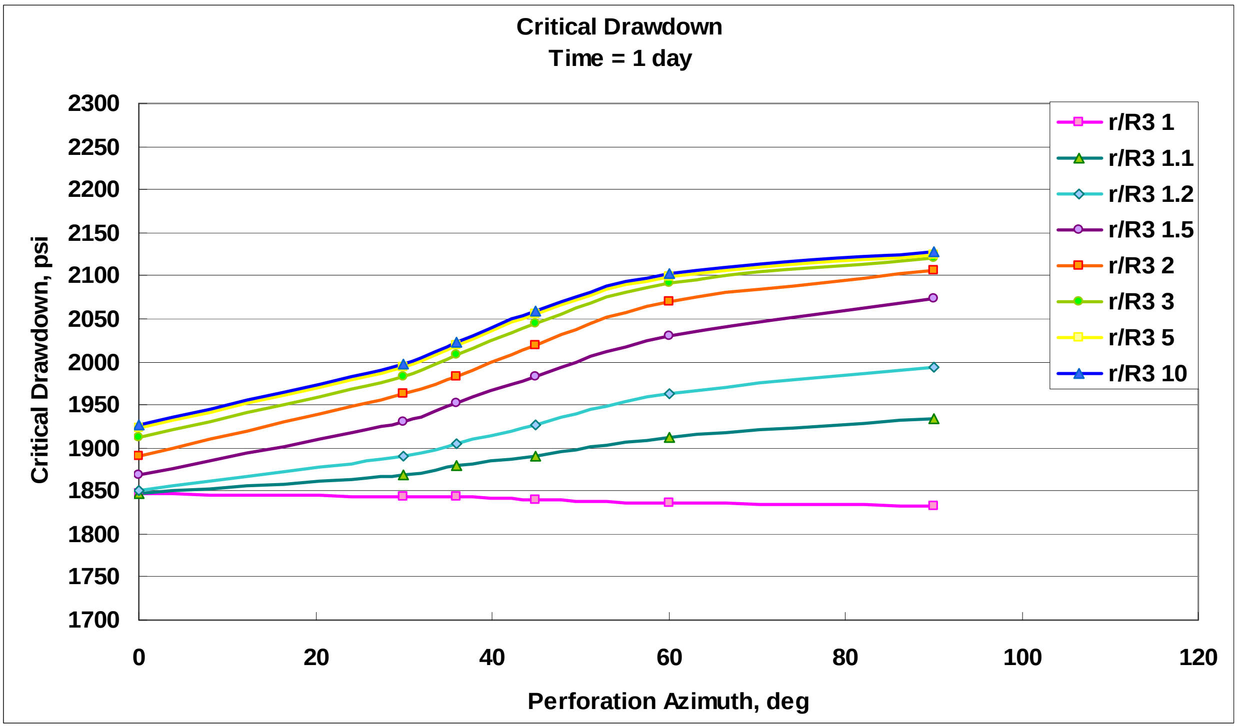

Figure 4.16: Case 5 critical drawdown pressure versus perforation azimuth fort t = 1 day, ratio of 1.2

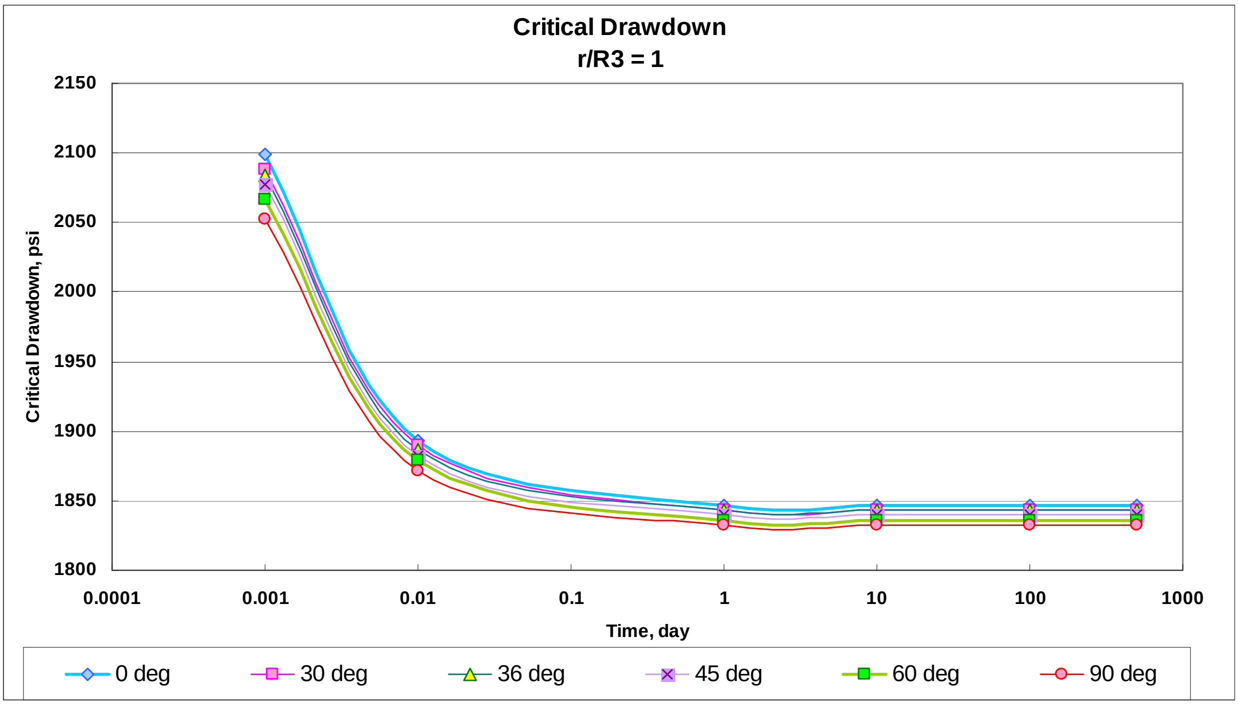

Figure 4.17: Case 5 critical drawdown pressure versus time after perforation for r/R3 = 1, ratio of 1.2

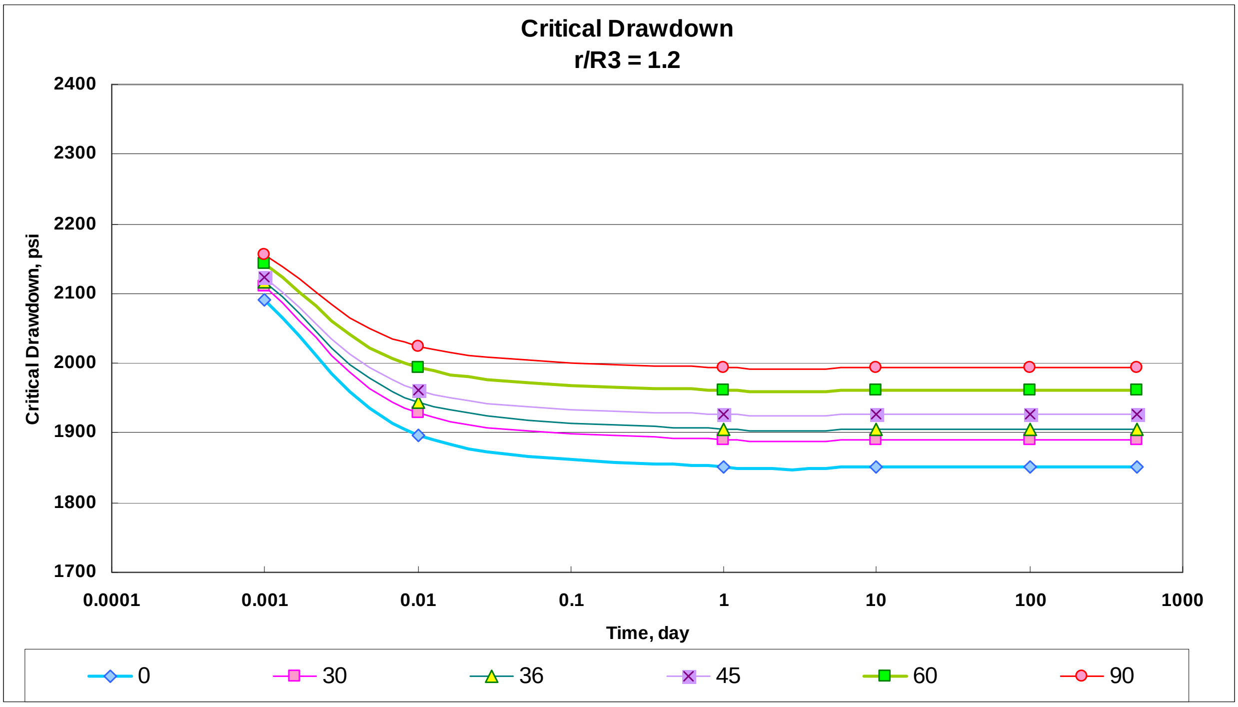

Figure 4.18: Case 5 critical drawdown pressure versus time after perforation for r/R3 = 1.2, ratio of 1.2

Figure 4.17 and 4.18 confirm that time after perforation greater than 0.01 day will not affect the critical drawdown pressure behavior but that radial distance from the wellbore will affect it.

4.1.4.3 Case 6 – the ratio of 1.4

In this case, the ratio between maximum and minimum horizontal stress is 1.4 but maintains the same values for all other parameters. Figure 4.19 shows that critical drawdown pressure at 0.001 day after perforation is within the range of 1820 – 1940 psi which is lower than the Base Case. Initially, the highest critical drawdown is not maintained at perforation in the direction of σ_h but the maximum number occurs at 60°.

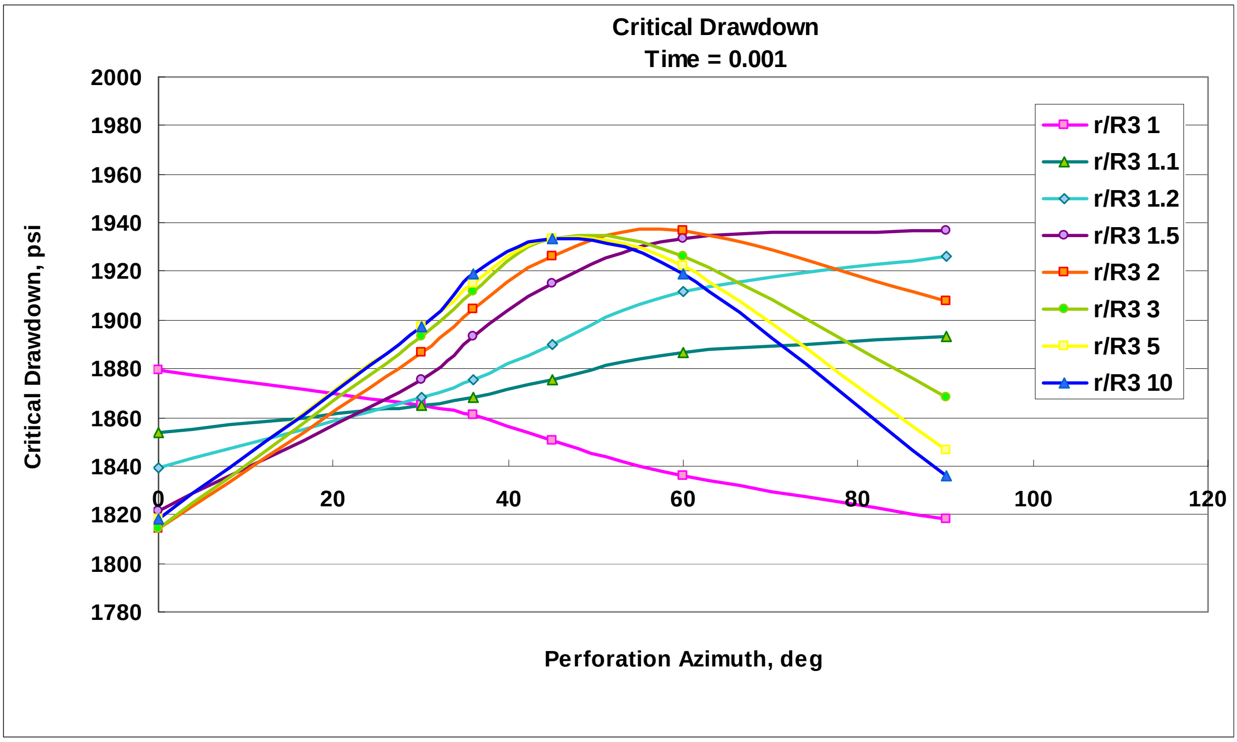

Figure 4.19: Case 6 critical drawdown pressure versus perforation azimuth for t = 0.001 day, ratio of 1.4

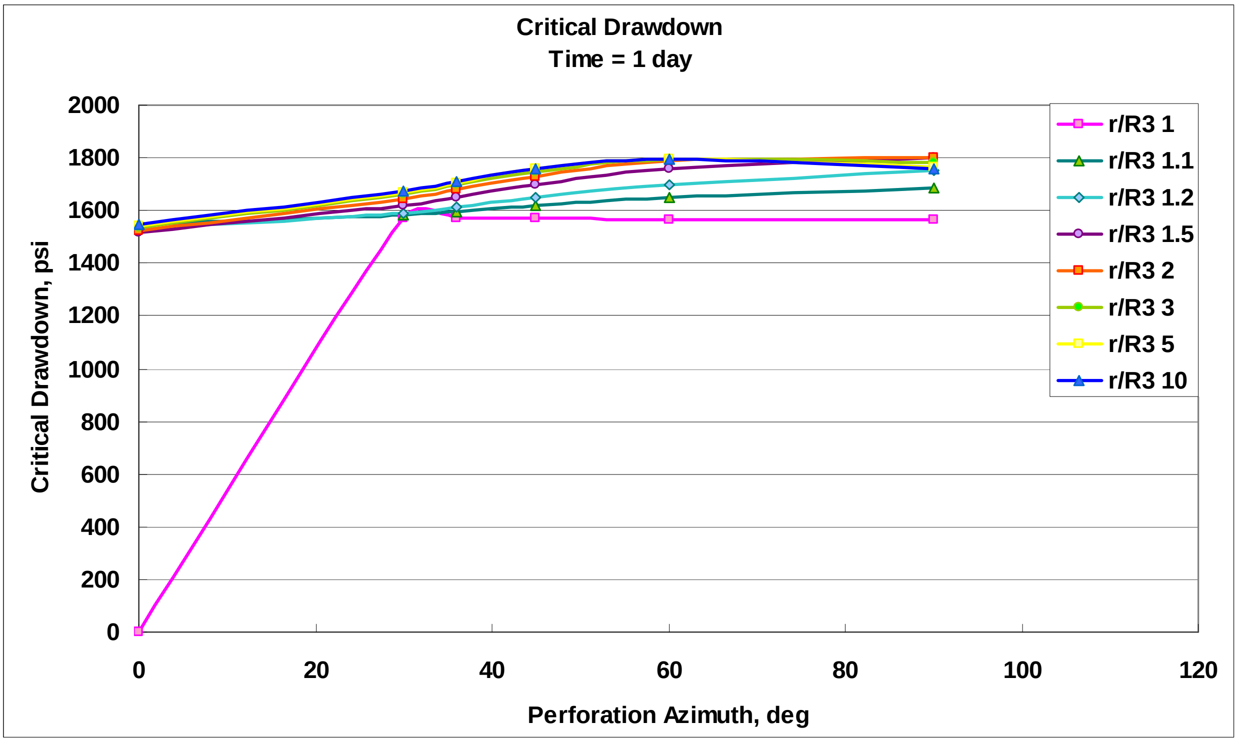

Figure 4.20: Case 6 critical drawdown pressure vs perforation azimuth for t = 1 day, ratio of 1.4

However, the different trend emerges in this case; a well produces hydrocarbon with sand when perforating at 0° of perforation azimuth as shown in Figure 4.20. Overall, the critical drawdown pressure is lower than in the Base Case and the perforation direction at the wellbore does not influence the critical drawdown pressure behavior.

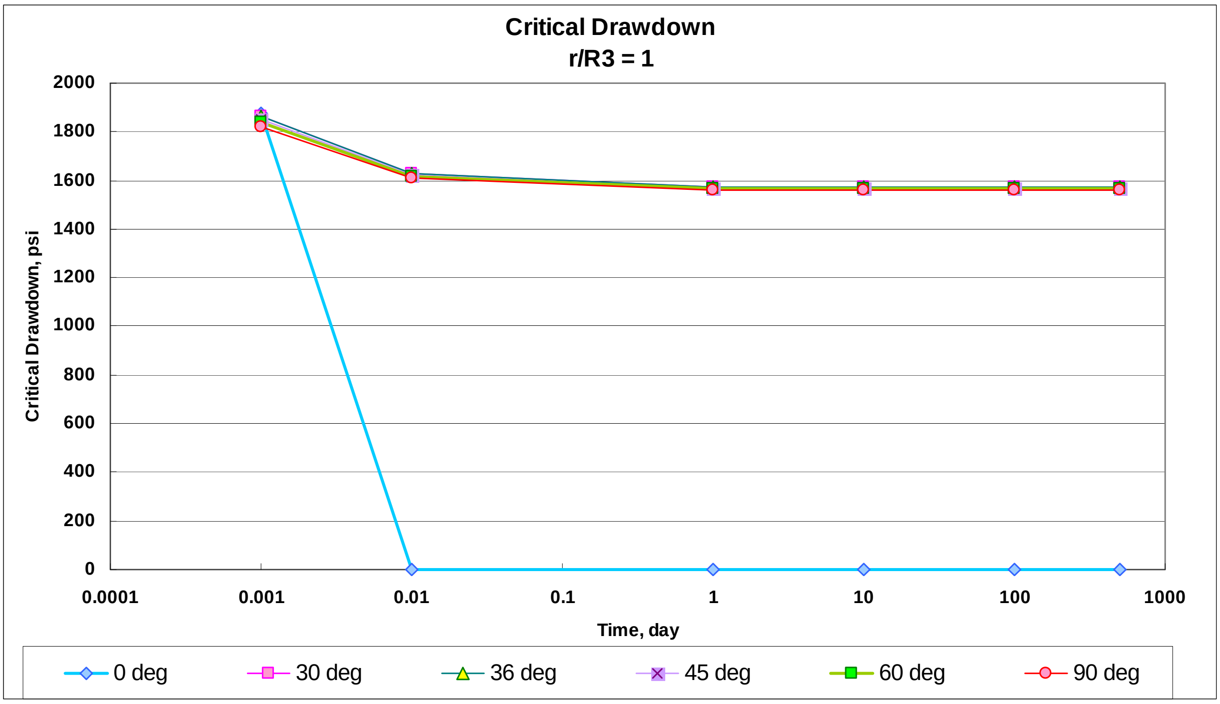

Figure 4.21: Case 6 critical drawdown pressure versus time after perforation for r/R3 = 1, ratio of 1.4

Perforation direction is not a significant parameter for critical drawdown pressure at the wellbore as shown in Figure 4.21; however, perforating in the direction of σ_H.is not suggested because a well will always contribute sand production. As the relative radial distance increases, critical drawdown pressure behavior curves differently for each perforation direction and results in the preferred perforation direction at σ_h as shown in Figure 4.22.

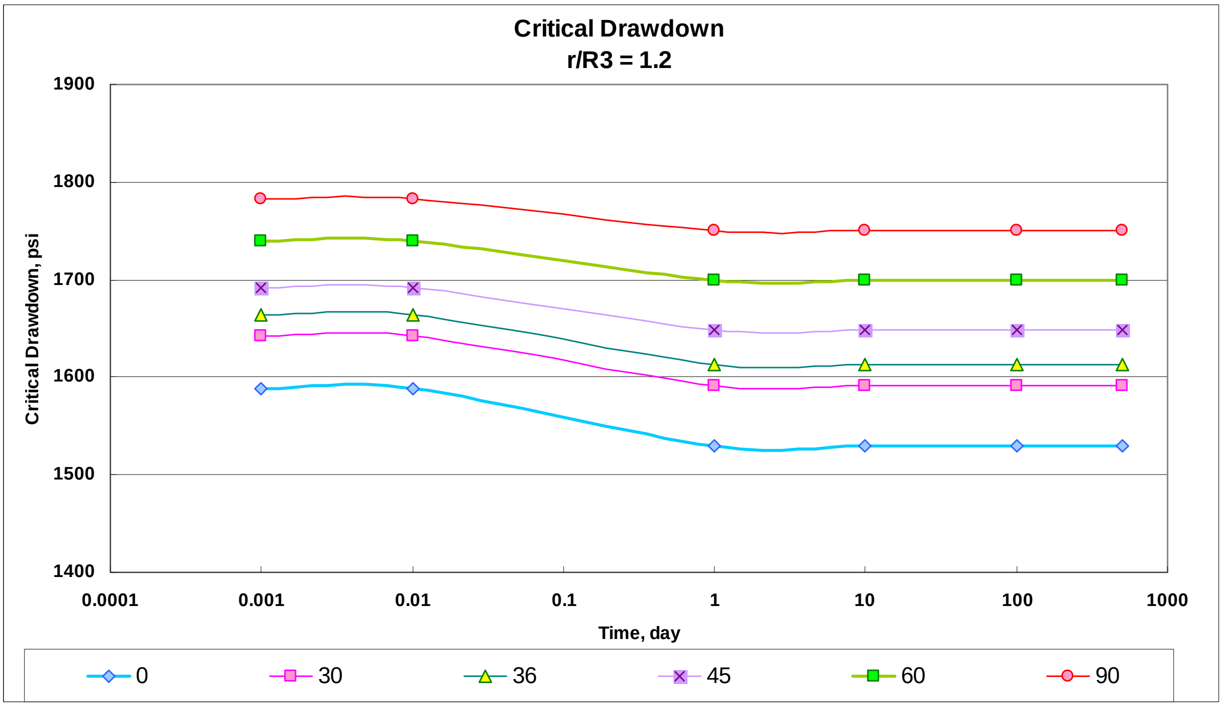

Figure 4.22: Case 6 critical drawdown pressure versus time after perforation for r/R3 = 1.2, ratio of 1.4

4.1.4.4 Case 7 – the ratio of 1.6

The ratio between maximum and minimum horizontal stress increases to 1.6 in this case. At near wellbore, a well will always produce sand when perforating directions are 0 and 90 degrees as shown in Figure 4.21 and 4.22. This graph shows that the possible critical drawdown at the maximum point is around 1800 psi. If some sand production is allowed, the perforation direction of 90° is necessary. Figure 4.25 confirms that some sand will be produced from a wellbore if perforating with a 90° perforation azimuth. However, this perforating direction is preferred when moving along a radial distance if the surface facility can handle some sand production as shown in Figure 4.25 and 4.26.

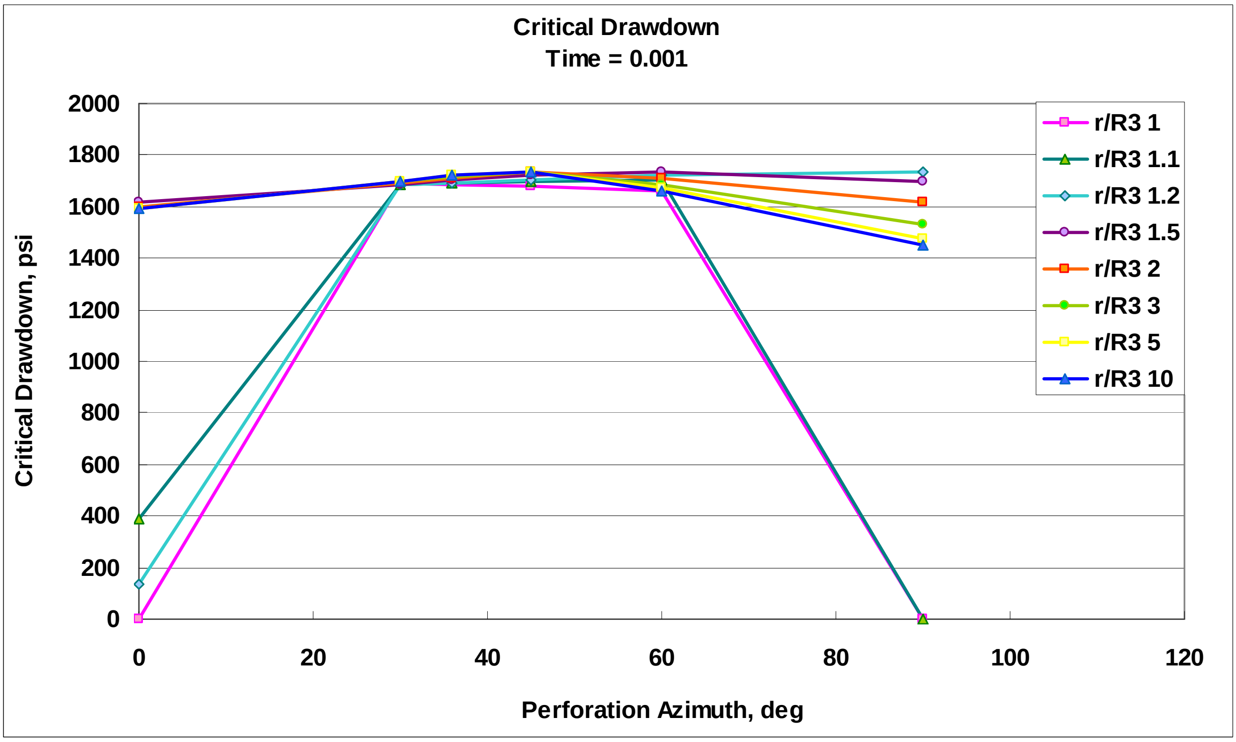

Figure 4.23: Case 7 critical drawdown pressure versus perforation azimuth for t = 0.001 day, ratio of 1.6

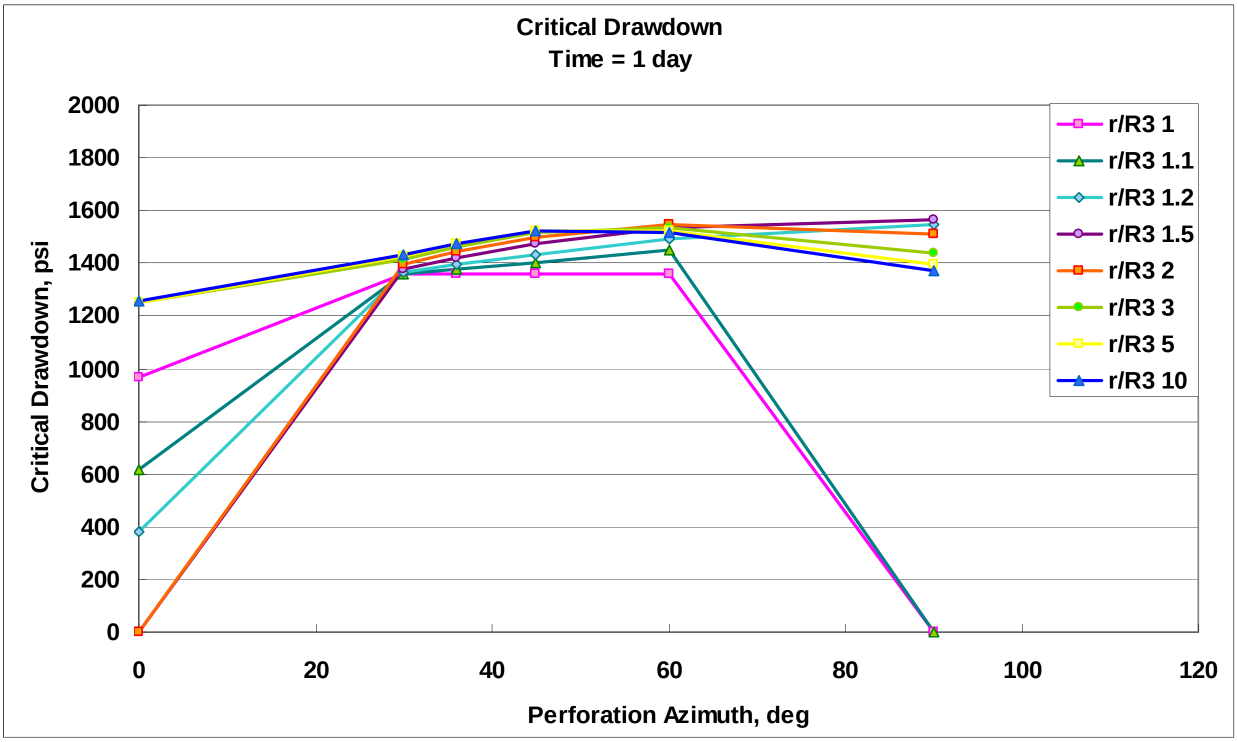

Figure 4.24: Case 7 critical drawdown pressure vs perforation azimuth for t = 1 day, ratio of 1.6

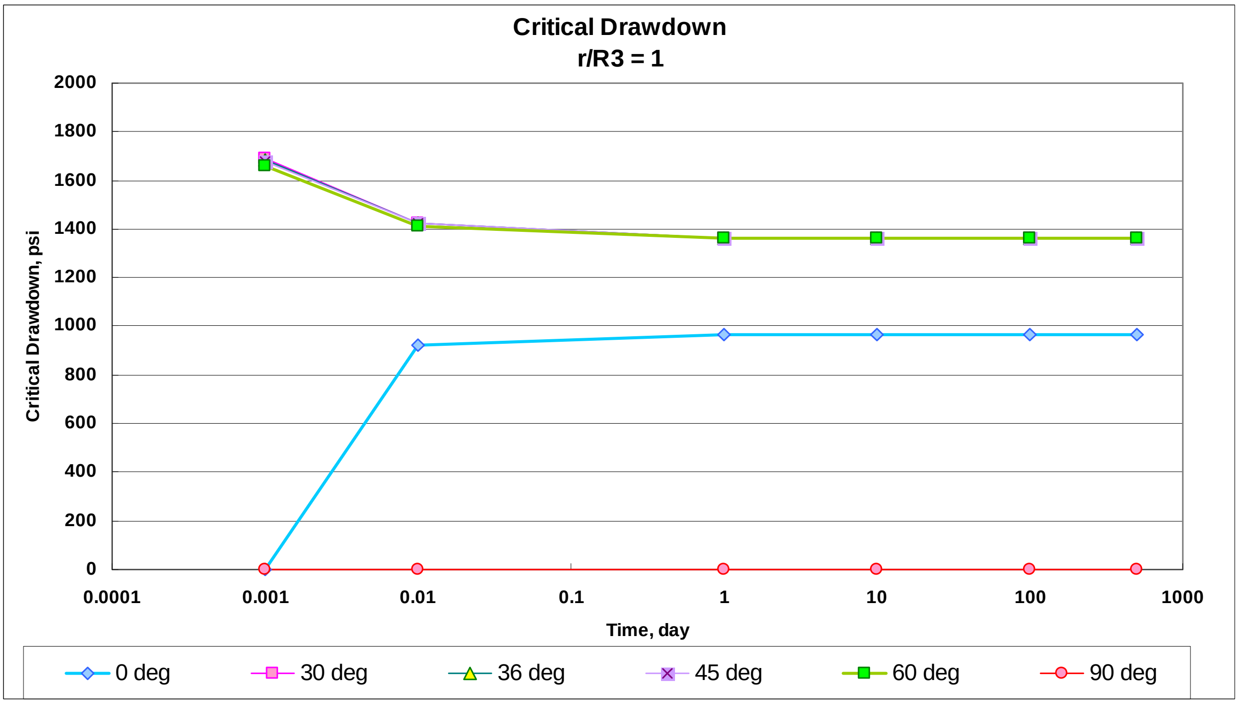

Figure 4.25: Case 7 critical drawdown pressure versus time after perforation for r/R3 = 1, ratio of 1.6

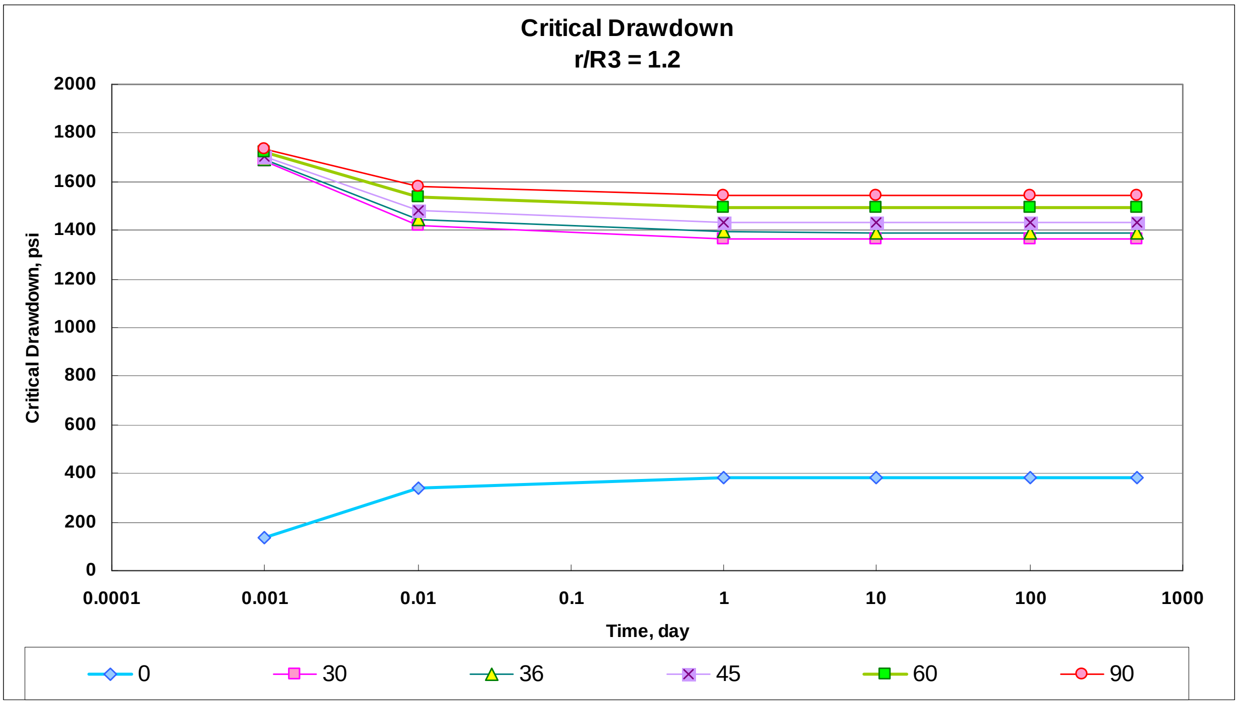

Figure 4.26: Case 7 critical drawdown pressure versus time after perforation for r/R3 = 1.2, ratio of 1.6

4.1.4.5 Case 8 – the ratio of 1.8

The ratio between maximum and minimum horizontal stresses in this case is 1.8, which results in a minimum horizontal stress of 0.50. The preferred perforation orientation of 90° now differs from the previous cases because sand production will be produced as time after perforation increases. Figure 4.27 and 4.28 agree with the statement above.

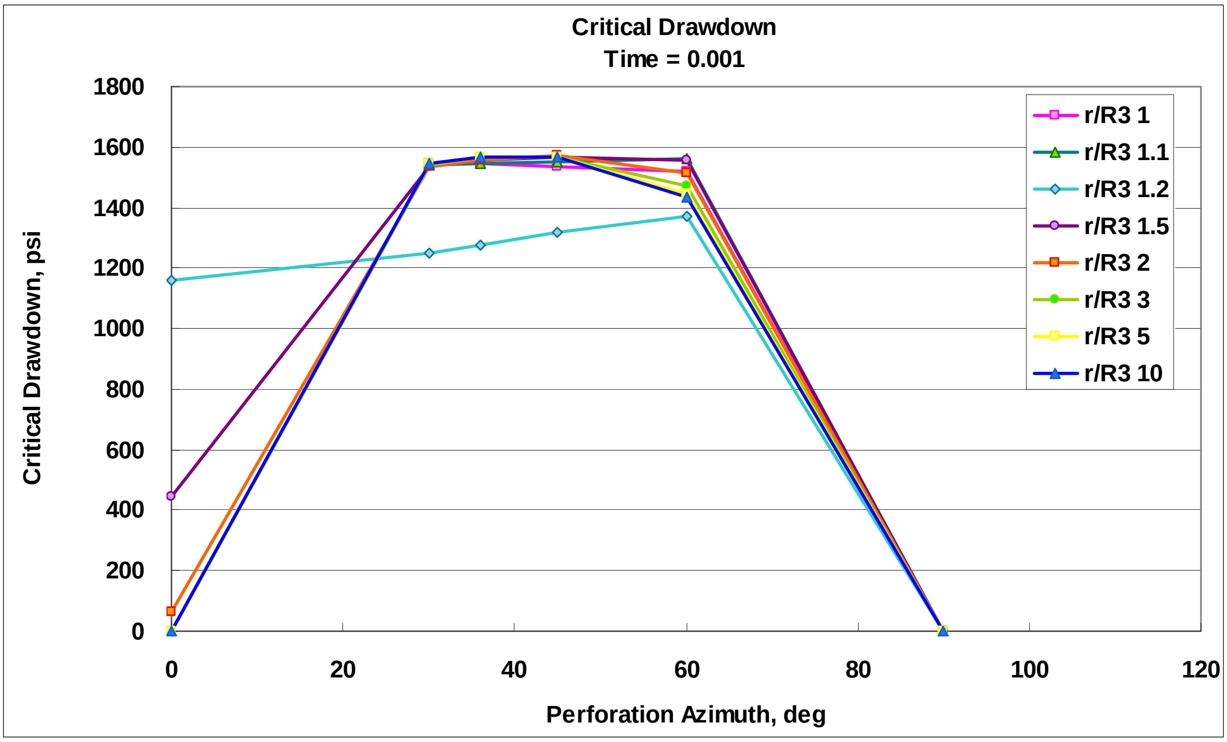

Figure 4.27: Case 8 critical drawdown pressure versus perforation azimuth for t = 0.001 day, ratio of 1.8

Instead, perforation at 45 or 60 degrees is recommended when minimum horizontal stress drops close to pore pressure. For this, pore pressure is 0.45 psi/ft while minimum horizontal stress is 0.50 psi/ft. Figures 4.29 – 4.33 plot the critical drawdown pressure and time after perforation for all perforation directions. These figures indicate that perforation direction at 90° will always create the risk of sand production while 0° causes sand production at only some distances and other perforation azimuths will generate lower sand production opportunities. In addition, the plots describe that time after perforation greater than 0.01 day does not have any effect on critical drawdown pressure behavior. This conclusion is in agreement with other cases including the Base Case.

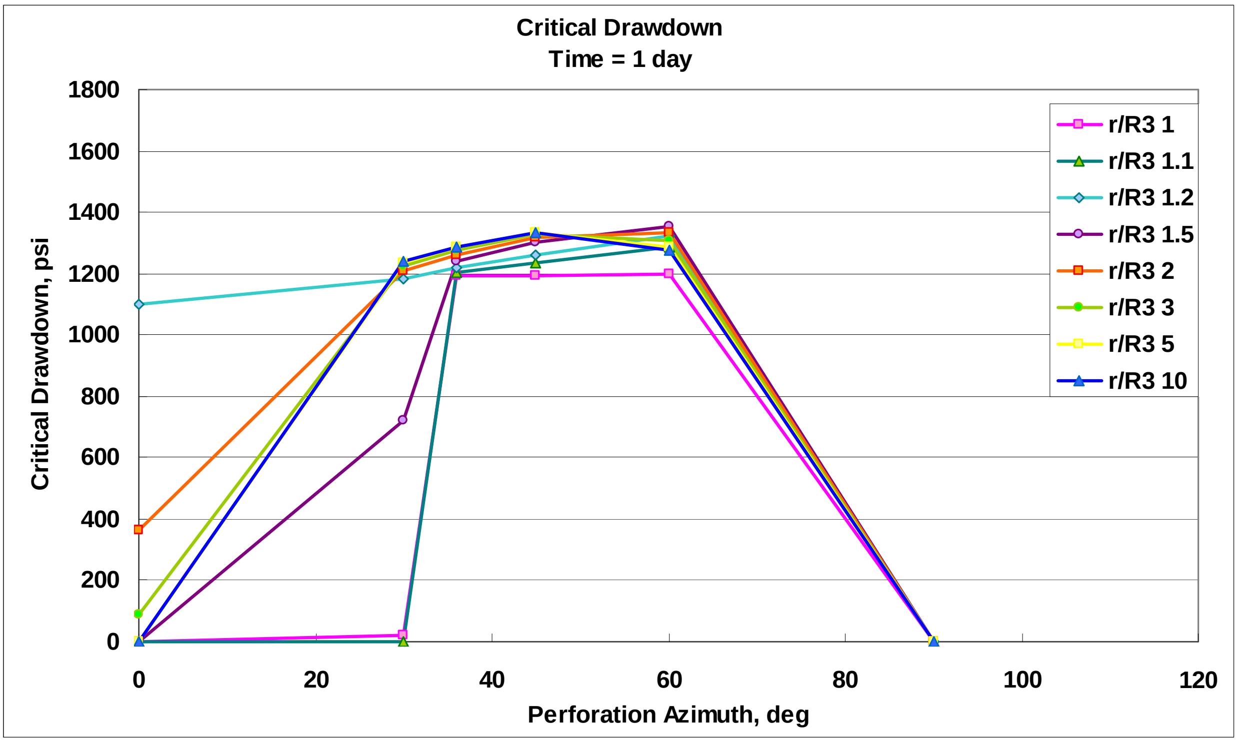

Figure 4.28: Case 8 critical drawdown pressure versus perforation azimuth for t = 1 day, ratio of 1.8

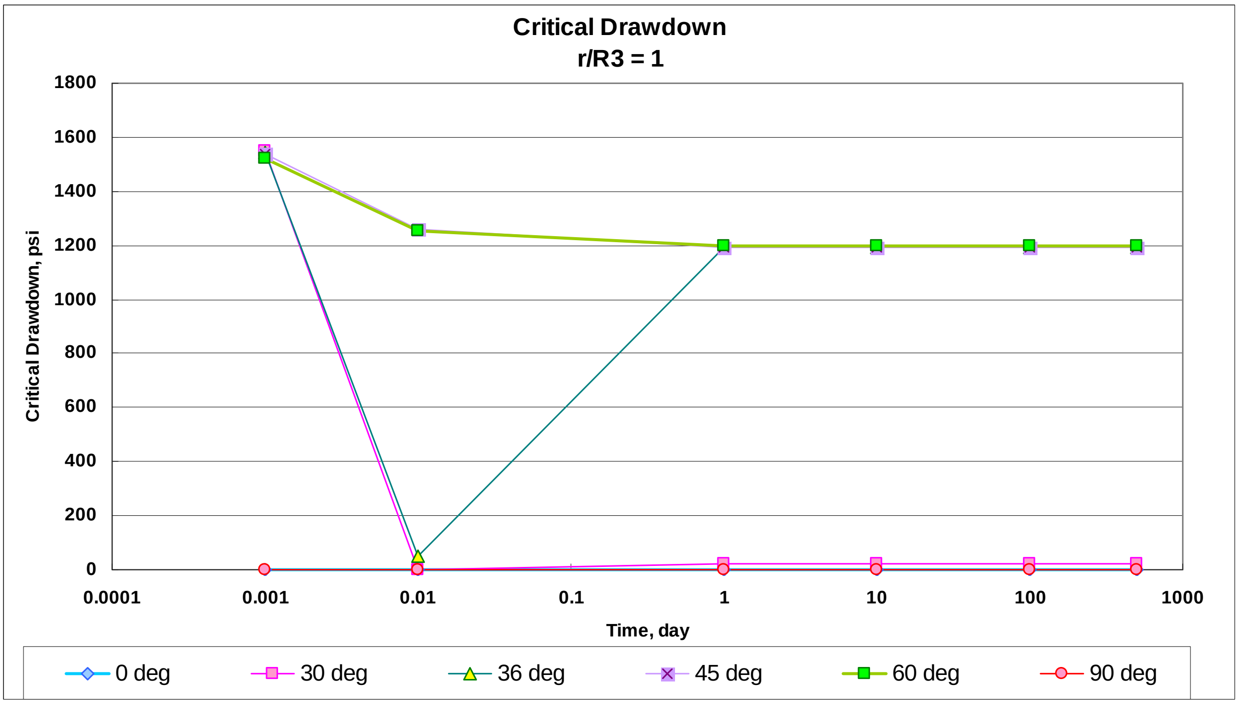

Figure 4.29: Case 8 critical drawdown pressure versus time after perforation for r/R3 = 1, ratio of 1.8

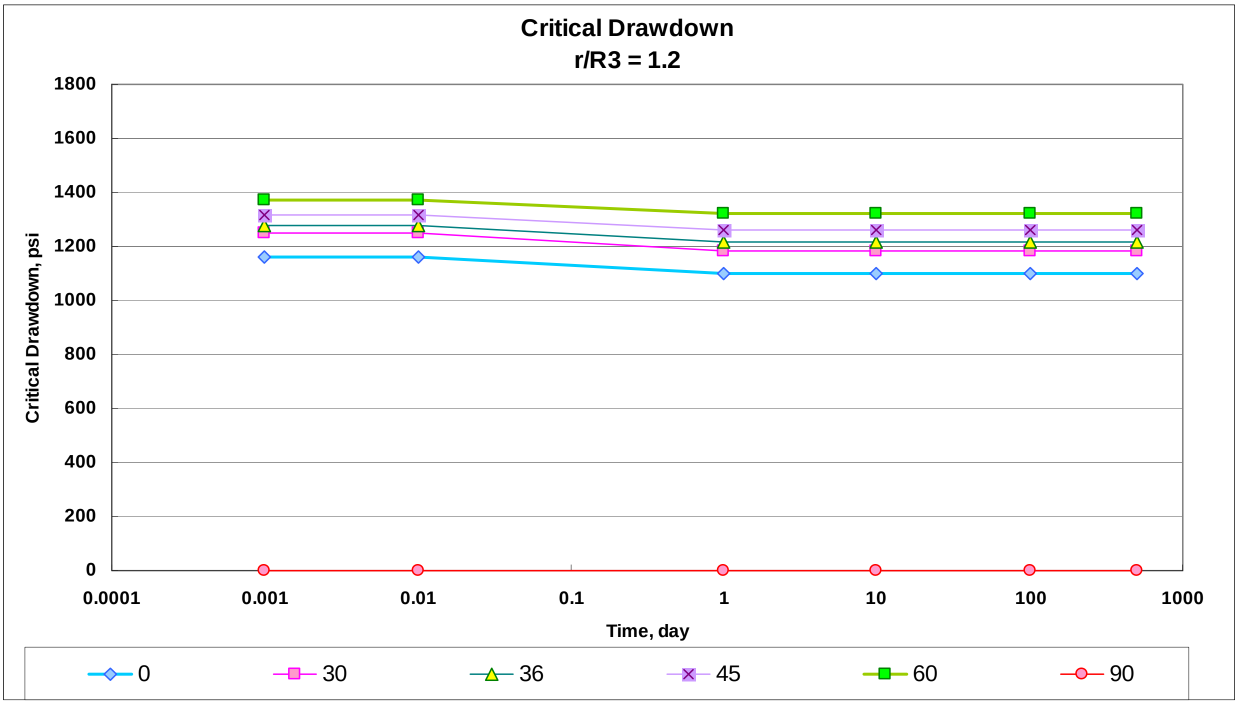

Figure 4.30: Case 8 critical drawdown pressure versus time after perforation for r/R3 = 1.2, ratio of 1.8

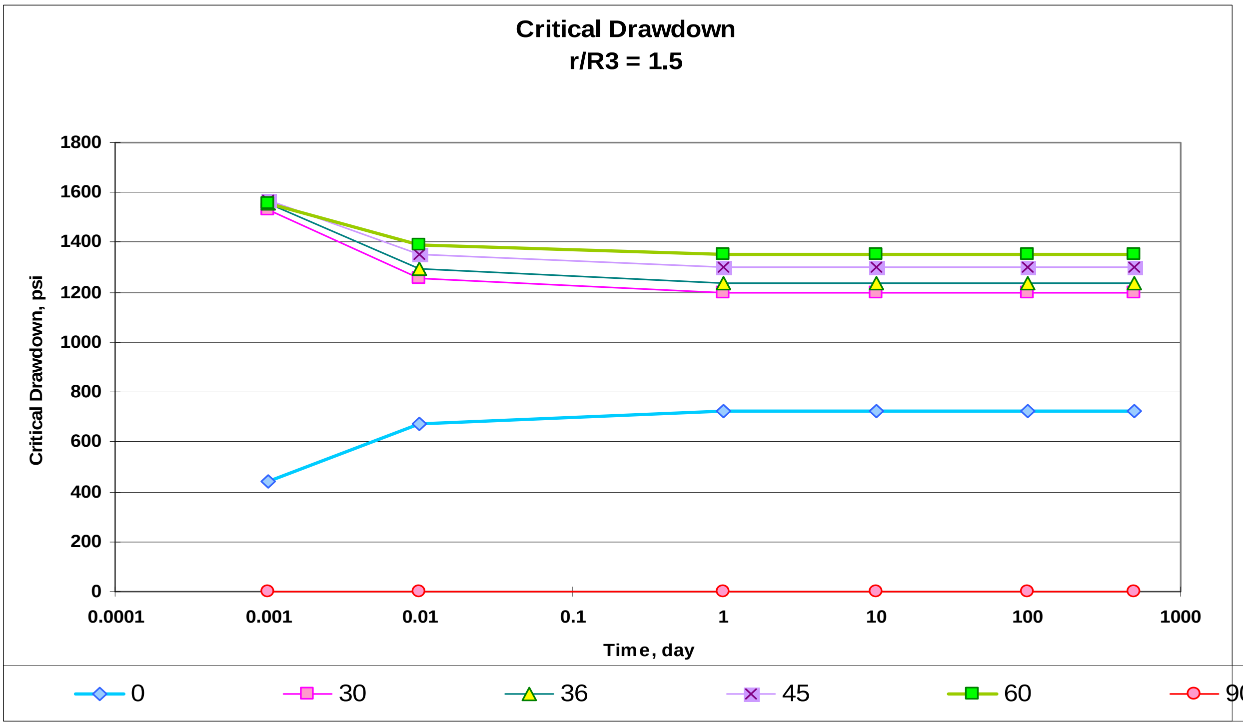

Figure 4.31: Case 8 critical drawdown pressure versus time after perforation for r/R3 = 1.5, ratio of 1.8

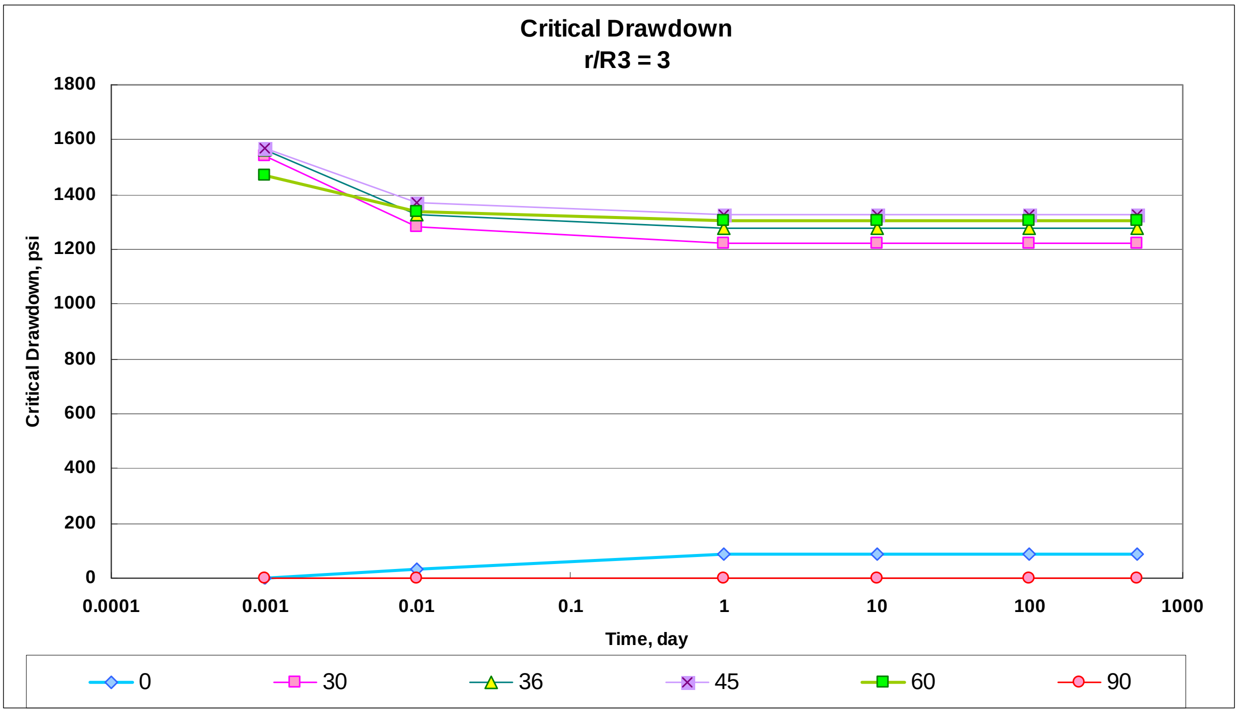

Figure 4.32: Case 8 critical drawdown pressure versus time after perforation for r/R3 = 3, ratio of 1.8

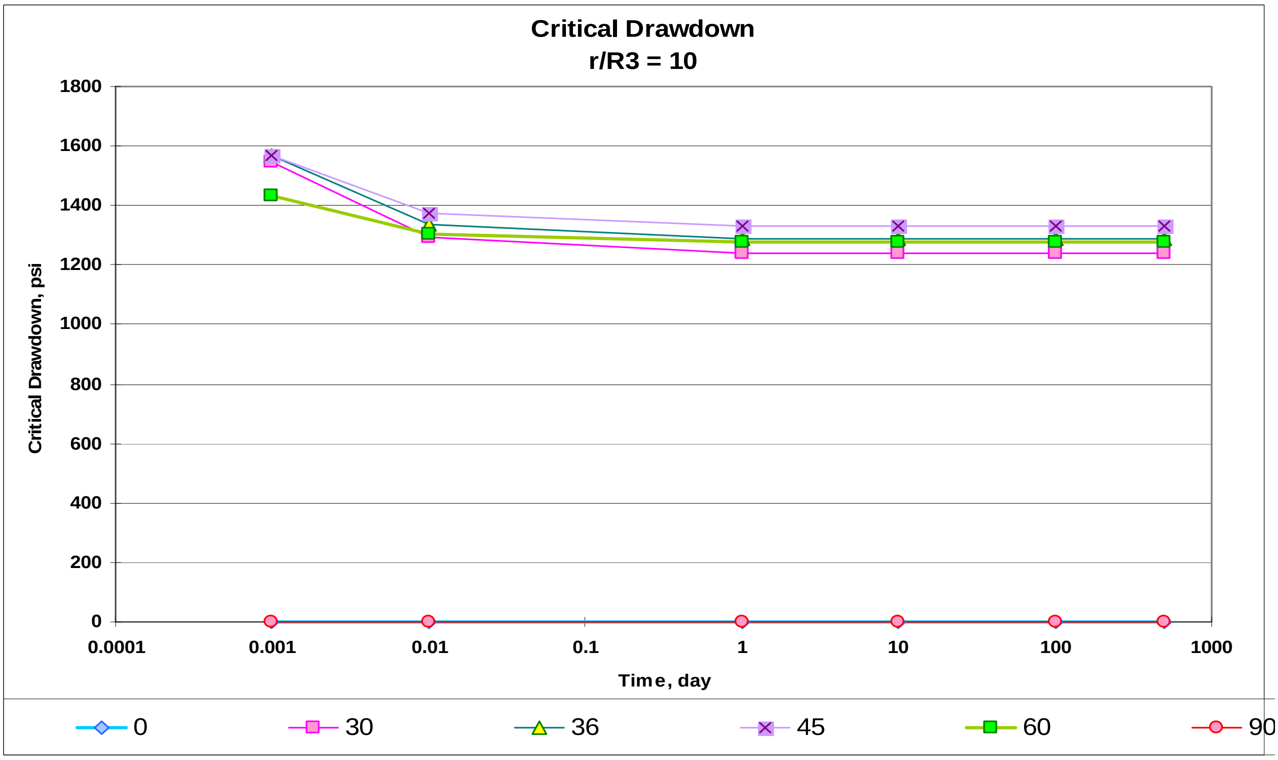

Figure 4.33: Case 8 critical drawdown pressure versus time after perforation for r/R3 = 10, ratio of 1.8

4.1.4.6 Case 9 – the ratio of 2.0

The minimum horizontal stress is identical to the pore pressure – 0.45 psi/ft, in this case. The result in this case is similar to Case 8 in which perforation direction at 90° is not suggested because rock will fail and create sand production to the wellbore as shown in Figures 4.34 and 4.35. All radial distances demonstrate that the perforation azimuth at 45° may be the best solution for this type of reservoir, see Figures 4.36 and 4.37. However, perforation azimuth at 60° is an alternative solution if some sand production is allowed at the wellbore.

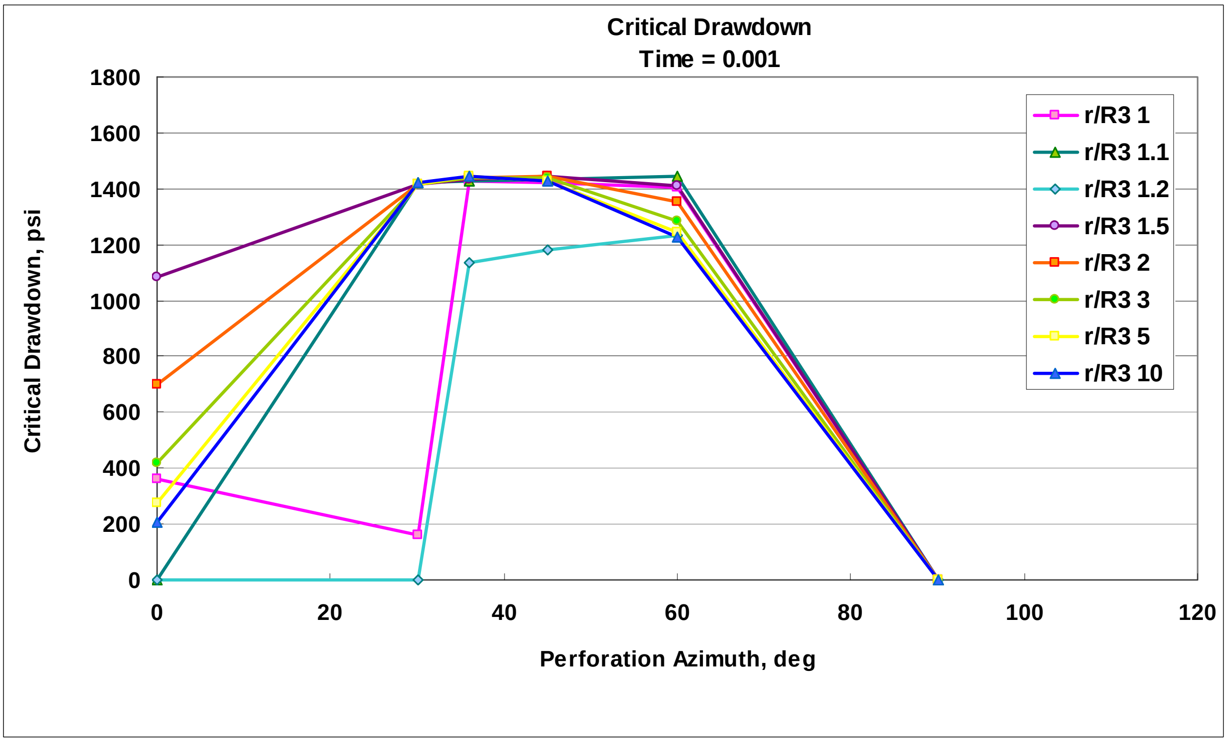

Figure 4.34: Case 9 critical drawdown pressure versus perforation azimuth for t = 0.001 day, ratio of 2.0

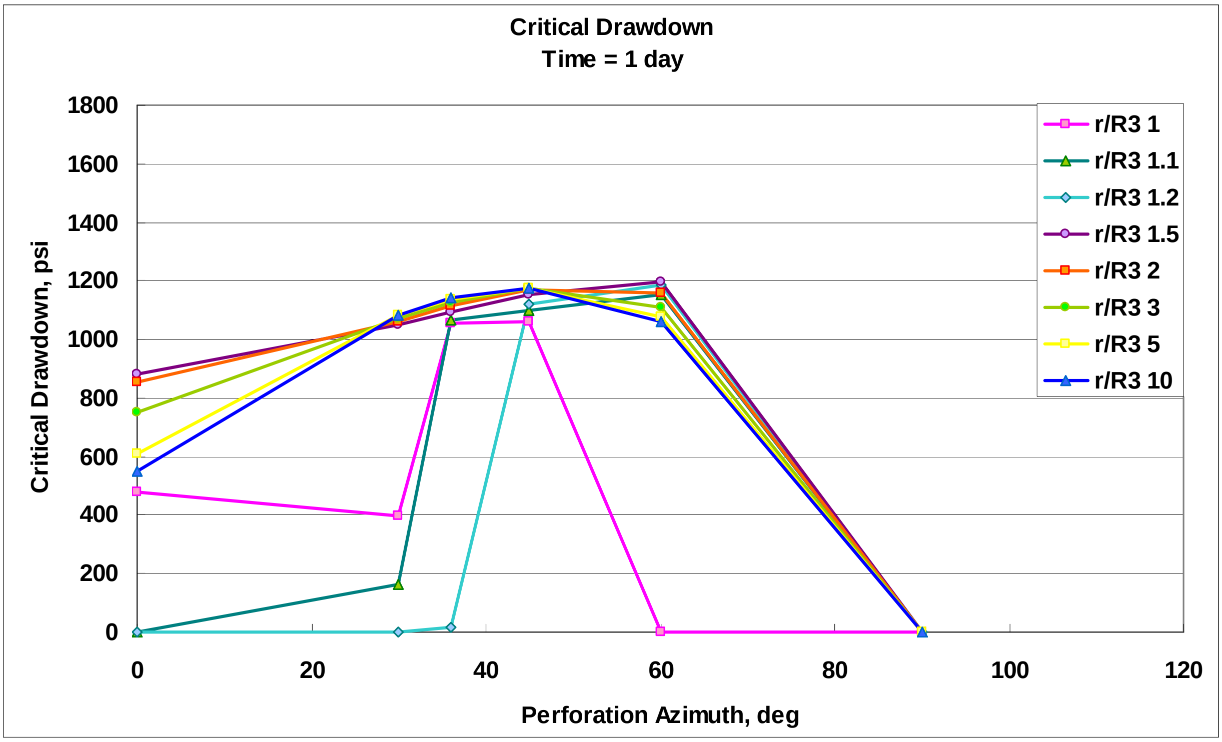

Figure 4.35: Case 9 critical drawdown pressure vs perforation azimuth for t = 1 day, ratio of 2.0

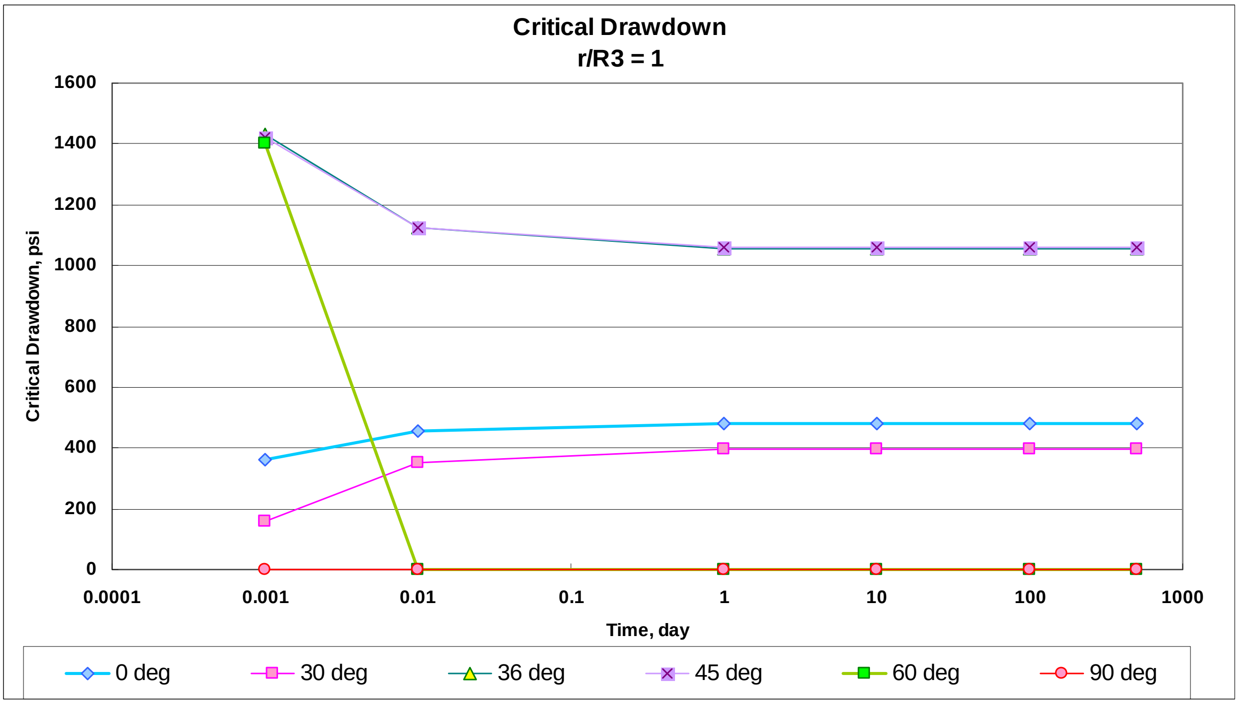

Figure 4.36: Case 9 critical drawdown pressure versus time after perforation for r/R3 = 1, ratio of 1.8

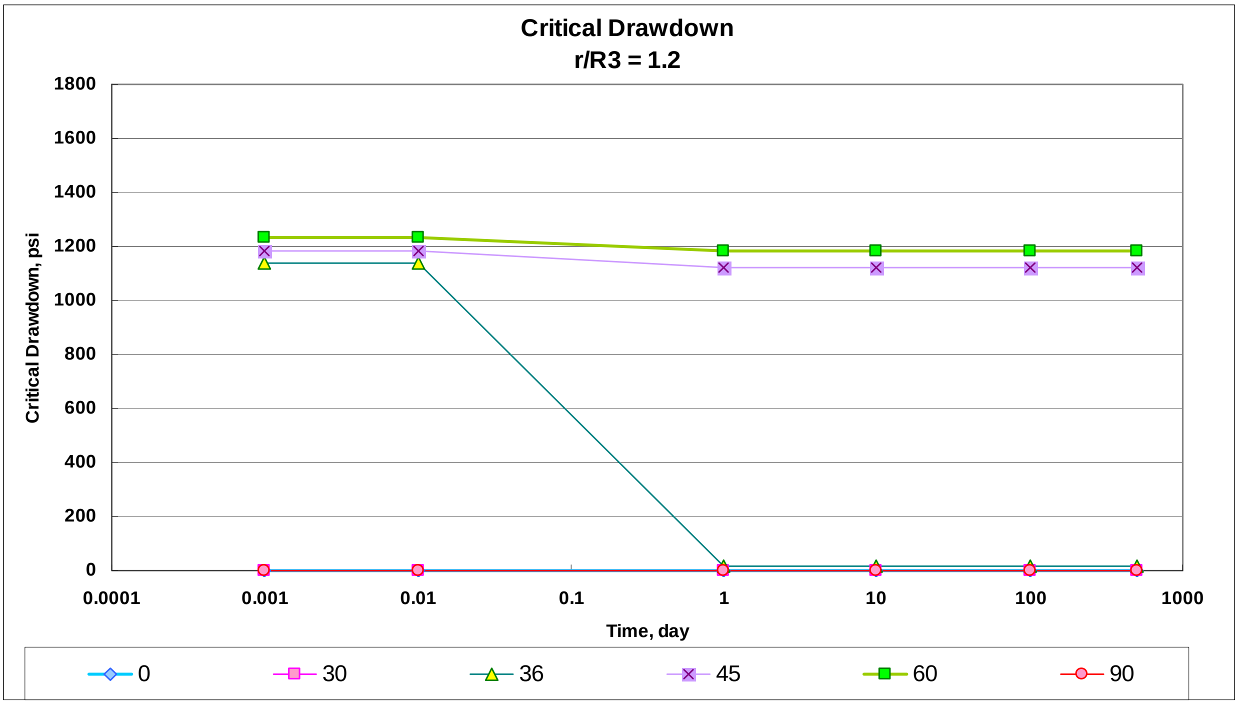

Figure 4.37: Case 9 critical drawdown pressure versus time after perforation for r/R3 = 1.2, ratio of 1.8

4.1.4.7 Case 10 – the ratio of 3.0

The minimum horizontal drawdown pressure is less than the pore pressure in this case. Figures 4.38 and 4.39 plot the critical drawdown pressure and the perforation azimuth. As can be seen, the graph does not have the pattern because tensile failure occurs when pore pressure is greater than the minimum horizontal stress. These two graphs indicate that a well will have a sand production problem from any perforation direction.

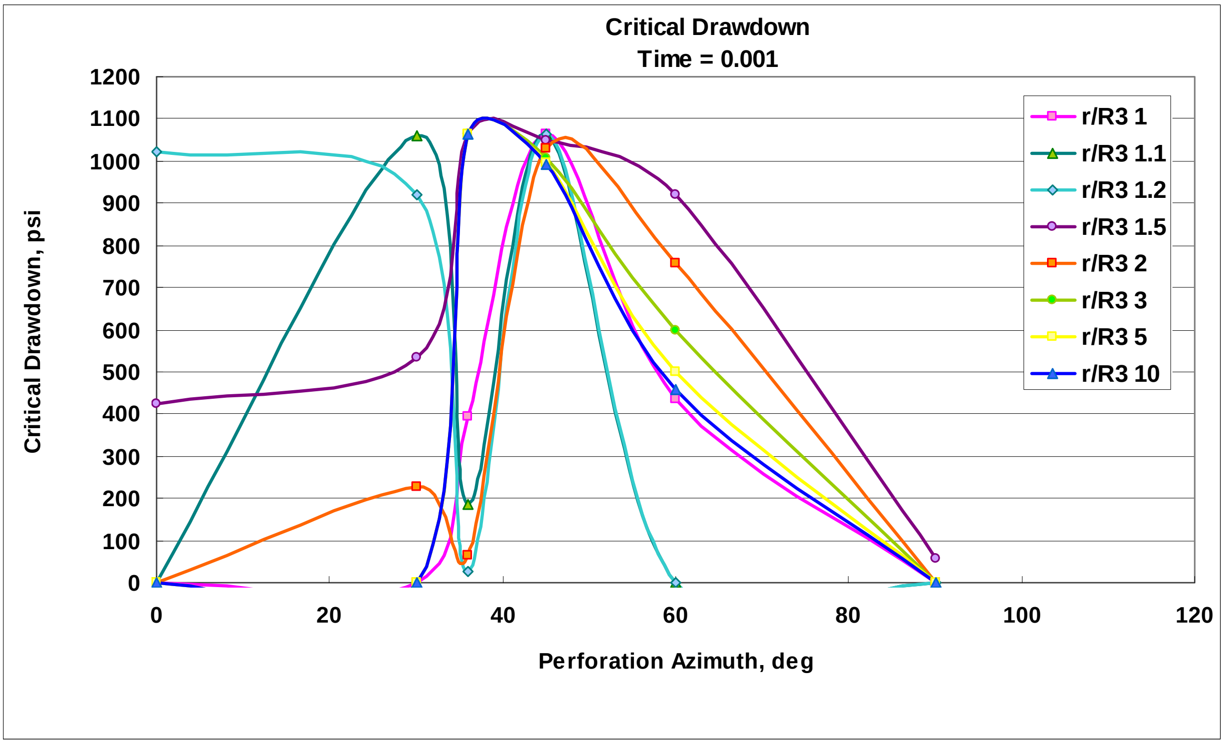

Figure 4.38: Case 10 critical drawdown pressure versus perforation azimuth for t = 0.001 day, ratio of 3.0

As a result, Case 10 can not be compared to the Base Case because this case creates tensile failure, which gives non-conclusive results as confirmed by Figure 4.39. Although time after perforation has increased, there is no influence on the critical drawdown pressure behavior and the pressure appears confusing.

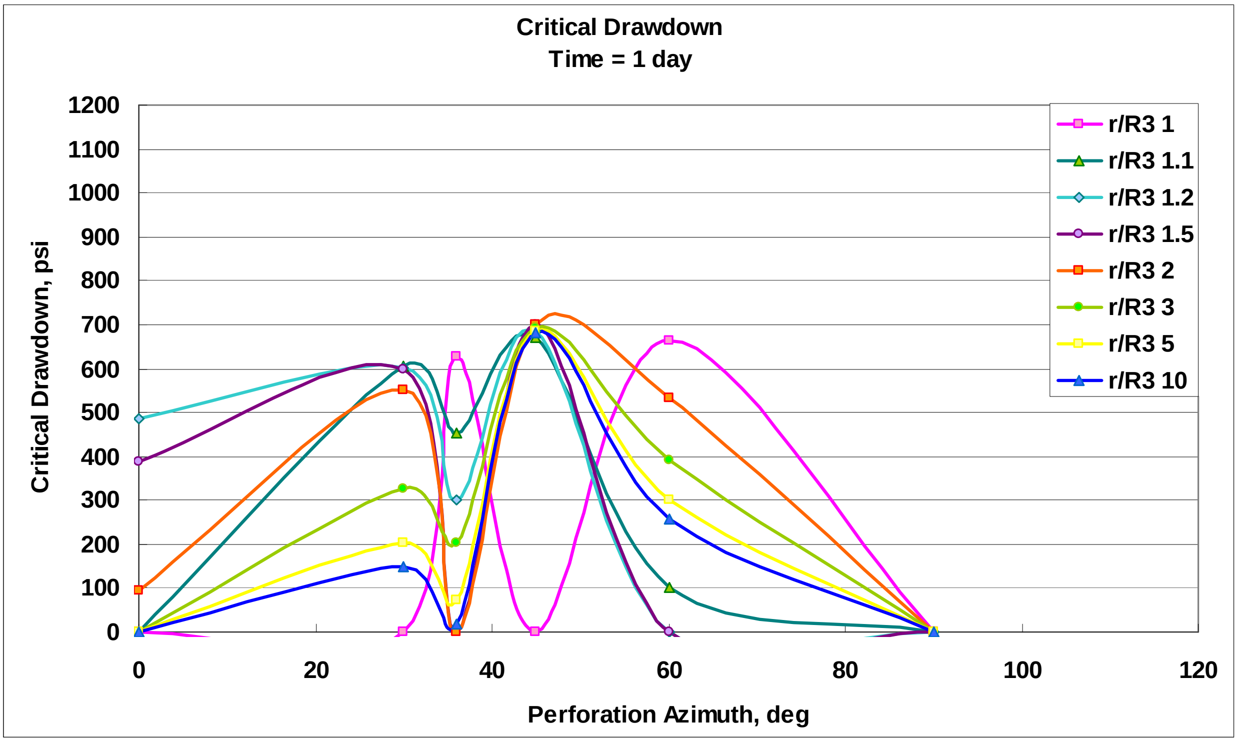

Figure 4.39: Case 10 critical drawdown pressure versus perforation azimuth for t = 1 day, ratio of 3.0

4.2 Analysis of parameter sensitivity

Parameters associated with critical drawdown pressure calculation were evaluated to locate the most significant factors for sand production prediction. Hence, knowing the importance of each parameter is useful when estimating critical drawdown pressure.

4.2.1 Data Input

A total of 26 parameters excluding perforation inclination were used: lower, middle, and upper limits; P10, P50, and P90. Then, the Base Case was calculated based on P50 of all parameters and compared to the value of P10 and P90. Table 4.2 displays the range of parameters input for this analysis.

Each parameter contains two results based on P10 and P90 values from one parameter with P50 of other parameters.

	Parameter		Input		
			P10	P50	P90
1	Po (Initial Pore Pressure)	psi/ft	0.25	0.35	0.4
2	Time	day	0.01	1	10
3	Wellbore Azimuth	deg	0	10	20
4	Wellbore Inclination	deg	0	10	20
5	Perforation Depth	ft	4950	5000	5150
6	Perforation Azimuth	deg	0	30	90
7	Perforation Inclination	deg	**90**	**90**	**90**
8	r/R3		1	1.2	2
9	R1 (Casing)	inch	2	2.5	3
10	R2 (Cement)	inch	2.8	3.1	3.5
11	R3 (Rock)	inch	3.4	3.6	3.84
12	SH (Max Hz Stress)	psi/ft	0.7	0.8	0.9
13	SHh (Ratio SH/Sh)		1.6	1.7	2
14	Sv (Vertical Stress)	psi/ft	0.9	0.93	0.98
15	E1 (Casing Young Modulus)	psi	2.4E+07	3.0E+07	3.6E+07
16	E2 (Cement Youung Modulus)	psi	2.0E+06	3.0E+06	3.5E+06
17	E3 (Rock Youung Modulus)	psi	2.0E+06	3.0E+06	1.0E+07
18	nu1 (Casing Poisson Ratio)		0.2	0.3	0.45
19	nu2 (Cement Poisson Ratio)		0.2	0.25	0.4
20	nu3 (Rock Poisson Ratio)		0.2	0.25	0.3
21	nuu (Undrainned Poisson Ratio)		0.3	0.4	0.5
22	B (Skempton coefficient)	0<B<1	0.3	0.6	1
23	Alpha (Biot - Willis coefficient)		0.6	0.8	1
24	eta (Poroelastic stress coefficient)		0.25	0.34	0.38
25	C (Consolidation coefficient/hydraulic diffusivity)	in^2/day	21.5	23.87	26.5
26	phi (Mohr-Coulomb friction angle)	deg	30	35	40
27	UCS (Rock Strength)	psi	3000	3300	3540

Table 4.2: Data Input for Parameter sensitivity Analysis

The numbers of P50 and P90 for each parameter are compared to its P50 number and plotted into percentage values as shown in Figure 4.40. As can be seen from the graph, the percentages of the widest data range are perforation azimuth, wellbore inclination, wellbore azimuth, and time after perforation.

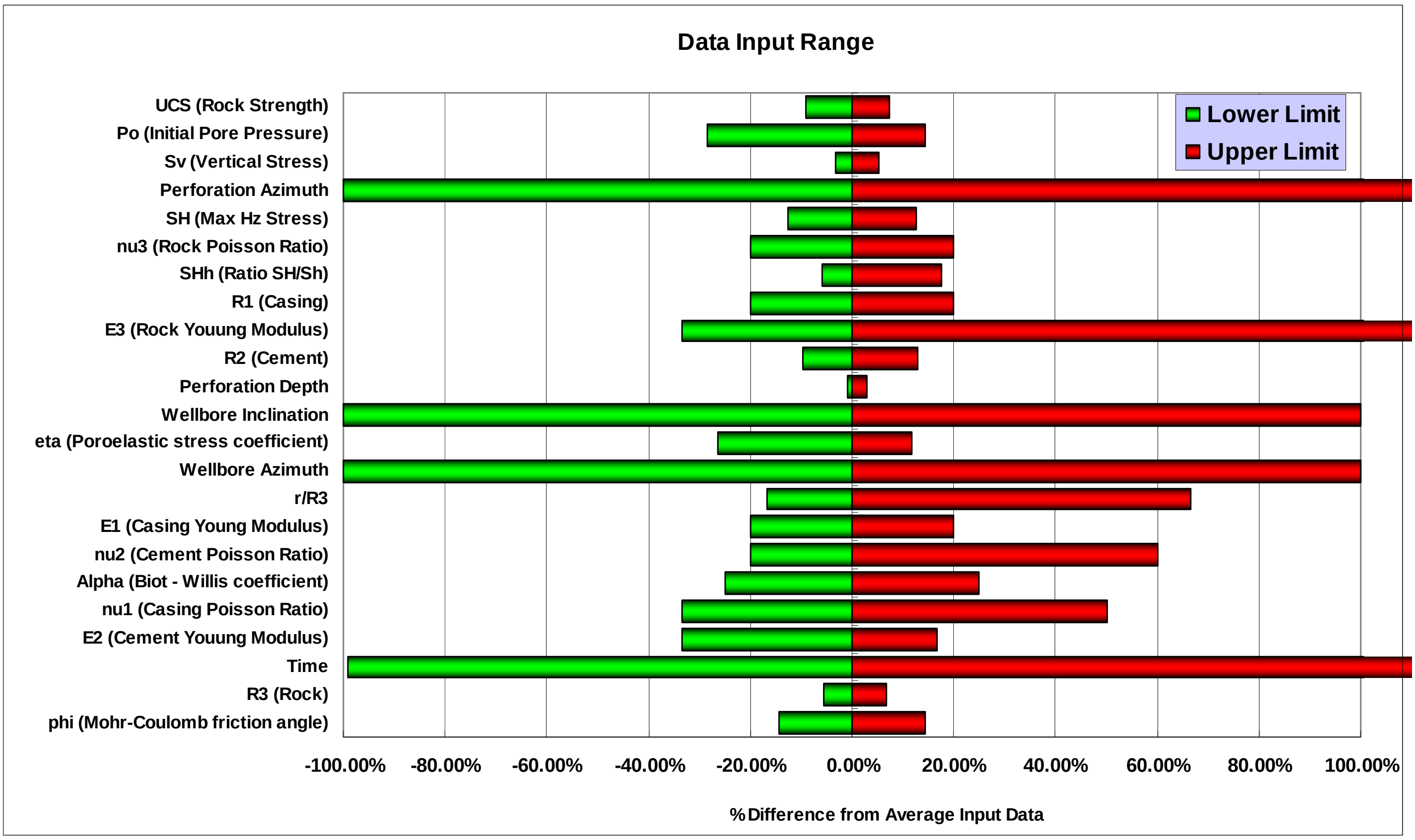

Figure 4.40: Percentage of data input compared to P50 number for each parameter

4.2.2 Results

Based on the study, the most significant parameters that impact the critical drawdown pressure calculations are UCS – rock strength, P_o – initial pore pressure, S_v – Vertical Stress, perforation azimuth, σ_H – maximum horizontal stress. These results are presented in Figure 4.41. The tornado chart shows that these five parameters significantly impact the critical drawdown pressure. These five parameters excluding perforation azimuth were assigned narrow ranges for sensitivity analysis. In other words, they obviously impact the critical drawdown pressure calculation with small number change.

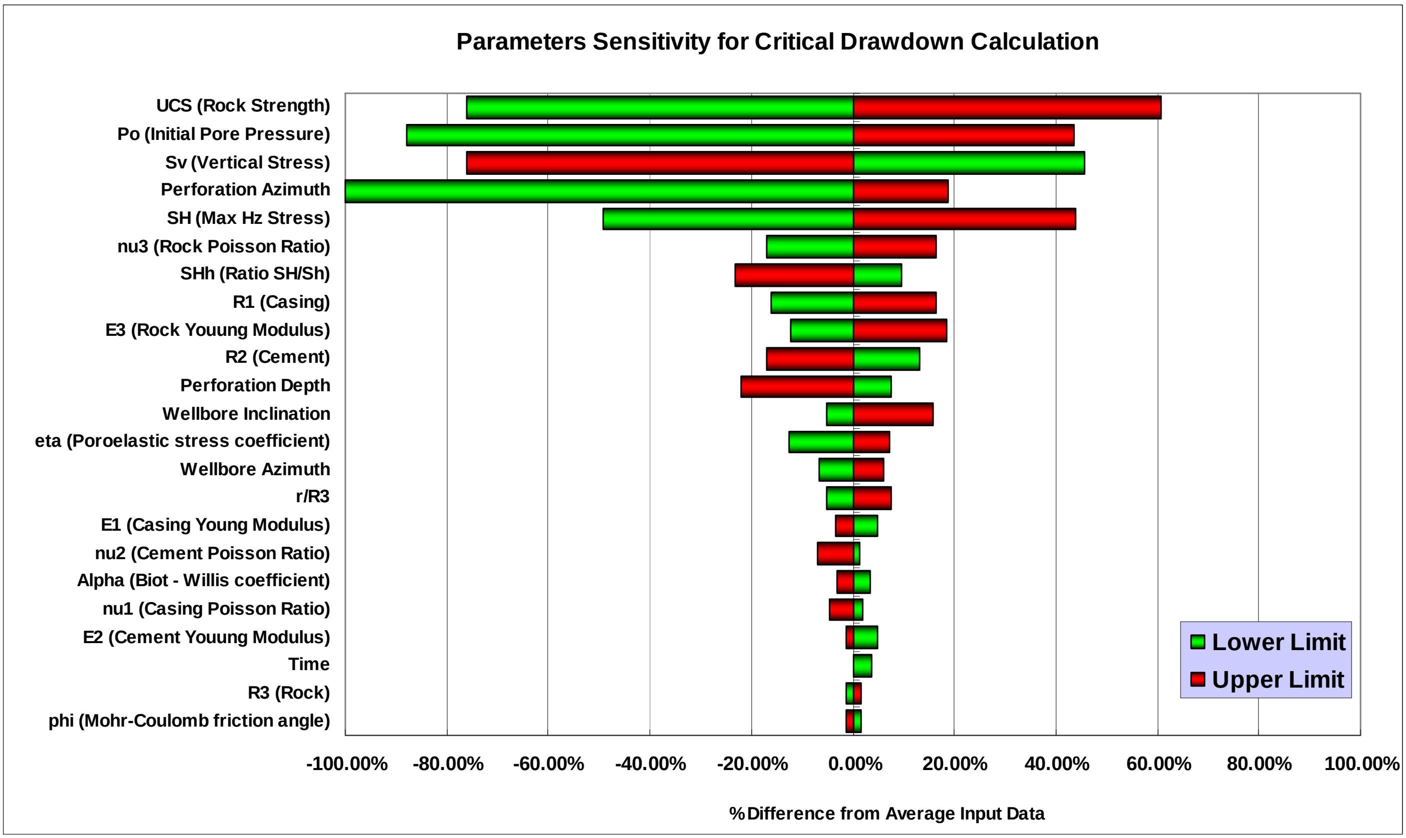

Figure 4.41: Tornado chart based on parameter sensitivity analysis

4.3 Discussion

Most results from the 10 different scenarios listed above agree on the perforation direction at σ_h when some sand production near the wellbore is allowed. Table 4.3 below illustrates the significant parameters which have been adjusted from the Base Case. Hence, this section will summarize all cases studied and compare to the Base Case.

Case	Wellbore Orientation		Perforation Orientation		Horizontal Stress		
	Azimuth	Inclination	Azimuth	Inclination	Maximum	Minimum	Ratio
Base Case	0	0	0-90	90	0.9	0.70	1.29
2	0	0	**0/90**	**30,45,60,90**	0.9	0.70	1.29
3	0	**10**	0-90	90	0.9	0.70	1.29
4	0	0	0-90	90	**0.7**	0.70	1.00
5	0	0	0-90	90	0.9	**0.75**	1.20
6	0	0	0-90	90	0.9	**0.64**	1.40
7	0	0	0-90	90	0.9	**0.56**	1.60
8	0	0	0-90	90	0.9	**0.50**	1.80
9	0	0	0-90	90	0.9	**0.45**	2.00
10	0	0	0-90	90	0.9	**0.30**	3.00

Table 4.3: Input summary for 10 cases

4.3.1 Preferred perforation orientation in Case 2 and Case 3 compared to the Base Case

A series of perforation inclinations were applied to Case 2 to determine the optimum perforation design that provides the maximum critical drawdown pressure. Simulation results confirm the perforation azimuth of 90° which is similar to the Base Case. However, a perforation inclination of 90° is safe at near wellbore and the critical drawdown pressure is lower than the perforation inclinations of 30, 45, 60 degrees when moving further from the wellbore. In addition, time after perforation does not alter the critical drawdown pressure behavior for all 4 perforation inclinations as shown in Figures 4.42 – 4.44. The critical drawdown pressure at the perforation inclination of 90°, remains close to the number at the wellbore, while the differences from the others range between 400 to 1000 psi for all samples of time after perforation.

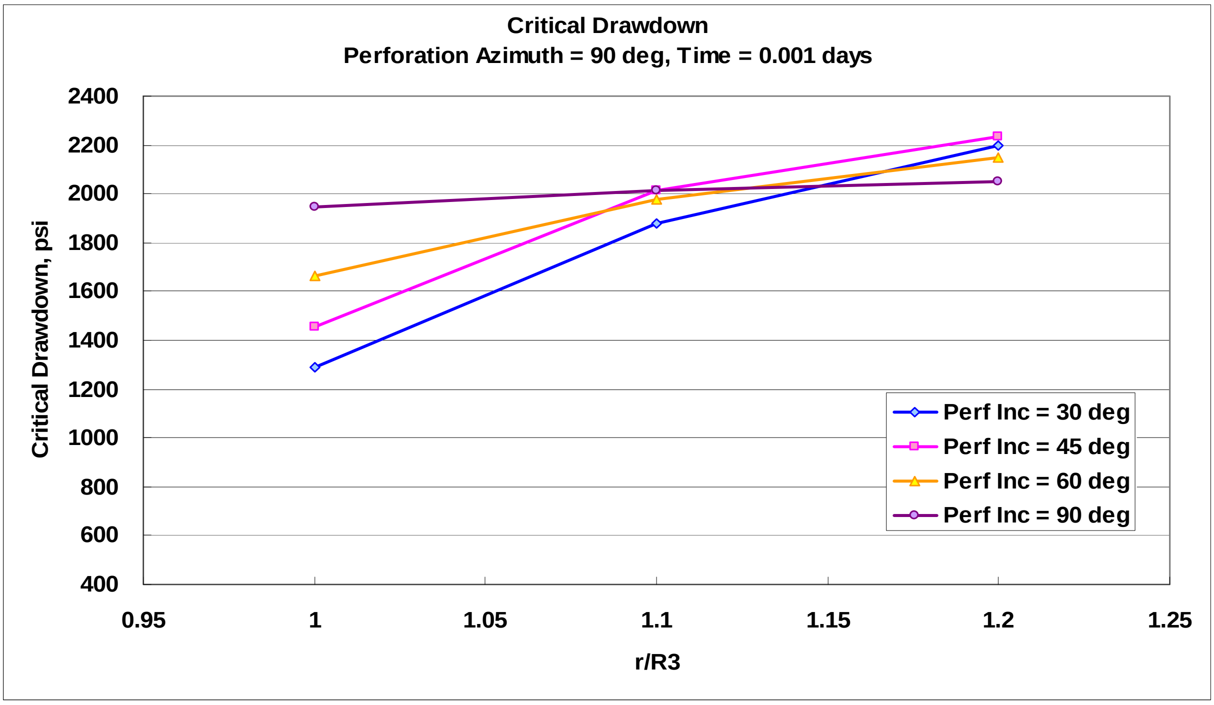

Figure 4.42: Critical drawdown pressure behavior for 4 different perforation inclinations at time after perforation of 0.001 day

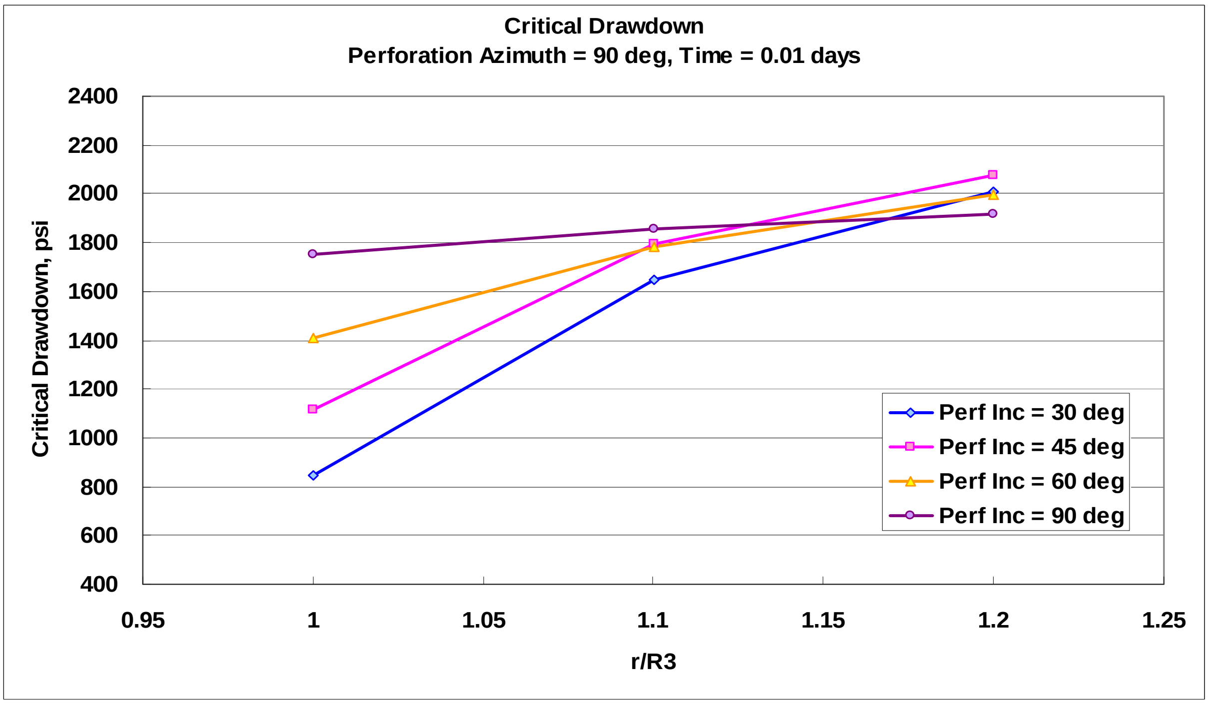

Figure 4.43: Critical drawdown pressure behavior for 4 different perforation inclinations at time after perforation of 0.01 day

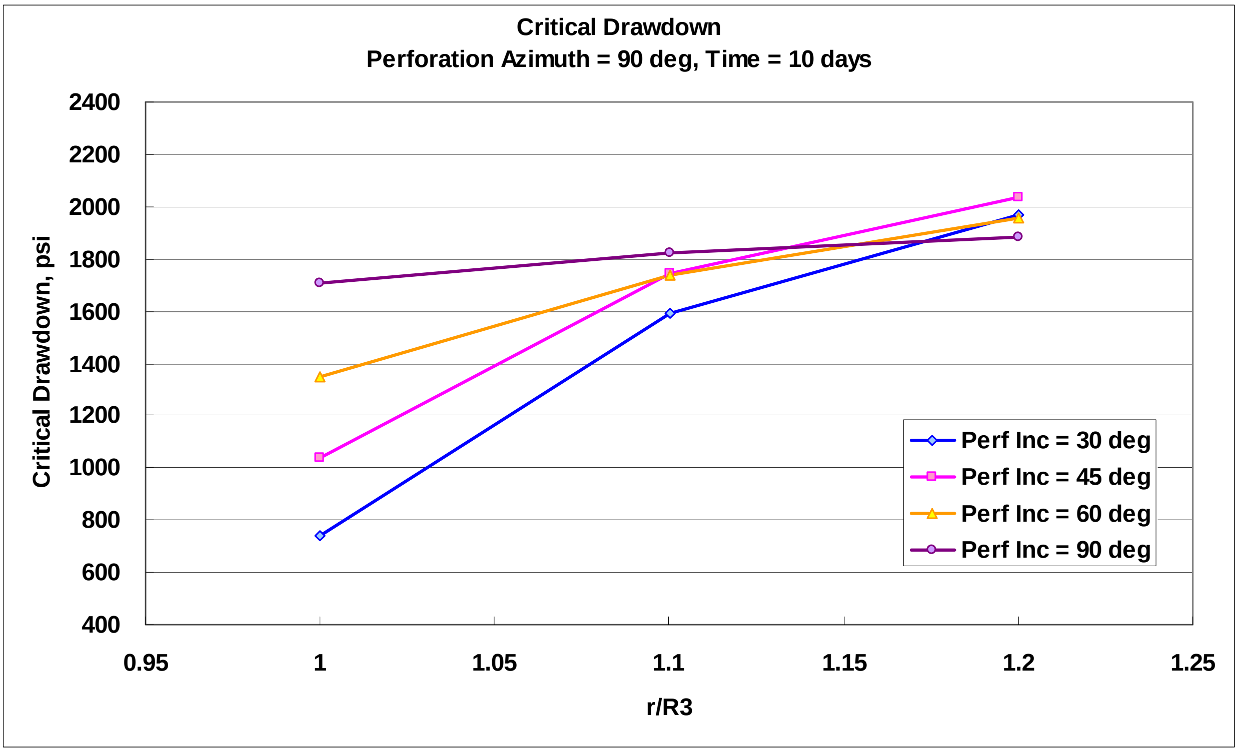

Figure 4.44: Critical drawdown pressure behavior for 4 different perforation inclinations at time after perforation of 10 days

Case 3 differs from the Base Case in that the well inclination is adjusted from 0° to 10° to define the risk of sand production when well inclination is increased. First, the results from the previous section show that this case creates slightly more risk of sand production compared to the Base Case. The overall critical drawdown pressure trend drops to around 50 psi compared to the Base Case. Second, the perforation direction of 90°(σ_h) is still the best alternative because it provides the maximum critical drawdown pressure which lowers the risk of sand production.

4.3.2 Preferred perforation orientation from Case 4 to 9 compared to the Base Case

The figure below illustrates the critical drawdown pressure behavior for Cases 4 to 9 compared to the Base Case. Time after perforation at 0.001 day is chosen to be the result sample.

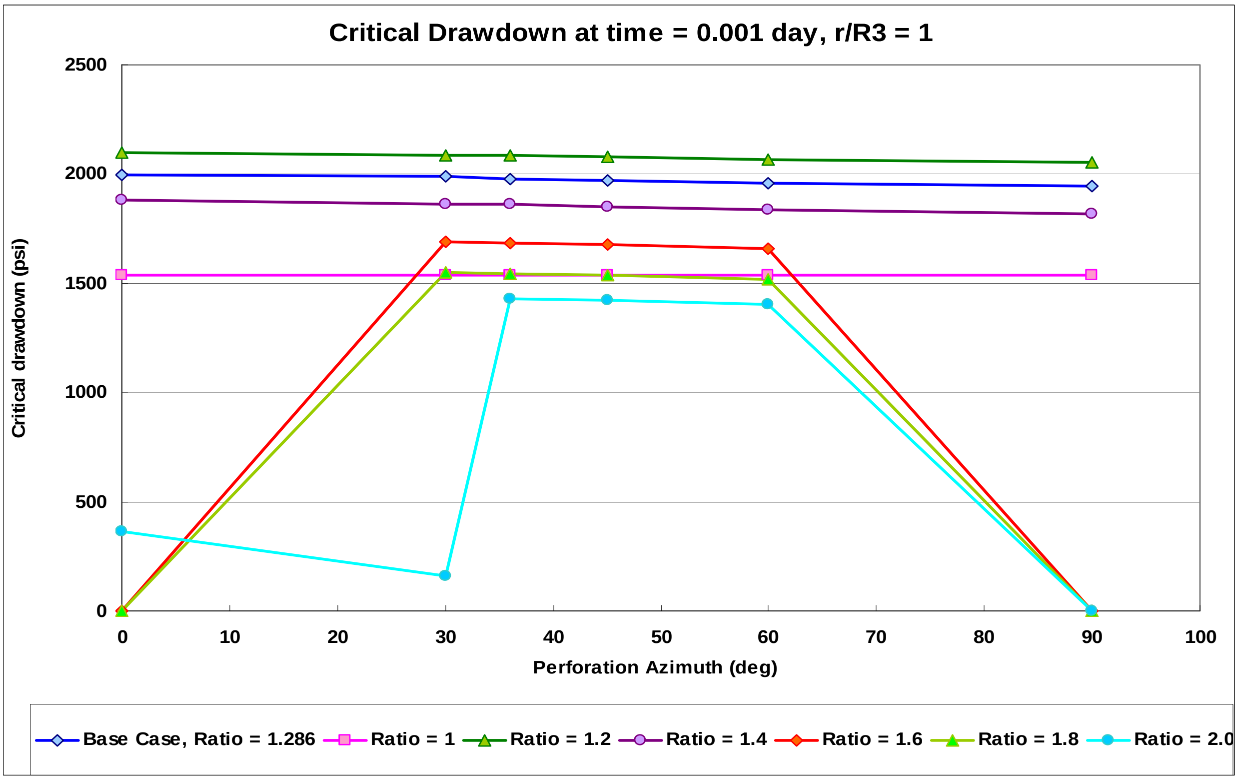

Figure 4.45: Critical drawdown for Case 4–9 compared to Base Case, time = 0.001 day

In Figures 4.45 – 4.49, critical drawdown pressure at time after perforation of 0.001 day with r/R_3 of 1, 1.1, 1.2, 1.5, 2 was selected. At wellbore in Figure 4.45, the plot shows that failure will occur at 0° and 90° when the ratio between maximum and minimum horizontal stresses is greater than 1.2.

Figures 4.46 and 4.47 agree that sand production will always occur further from the wellbore when the ratio is greater than 1.6 with a perforation azimuth of 90°. Shear stress around the perforation tunnel is possibly promoted by the increase in the difference between maximum and minimum horizontal stresses. Then, these higher shear stresses are likely to lead sand production into the wellbore [17]. As a result, the optimal perforation azimuth needs to be 45° and 60° when the rock has a ratio greater than 1.4. Moreover, the perforation azimuth of 90° still provides the maximum critical drawdown for the rock with the ratio lower than 1.4. The overall critical drawdown pressure trend is highest at the ratio of 1.2 and decreasing as the ratio increases.

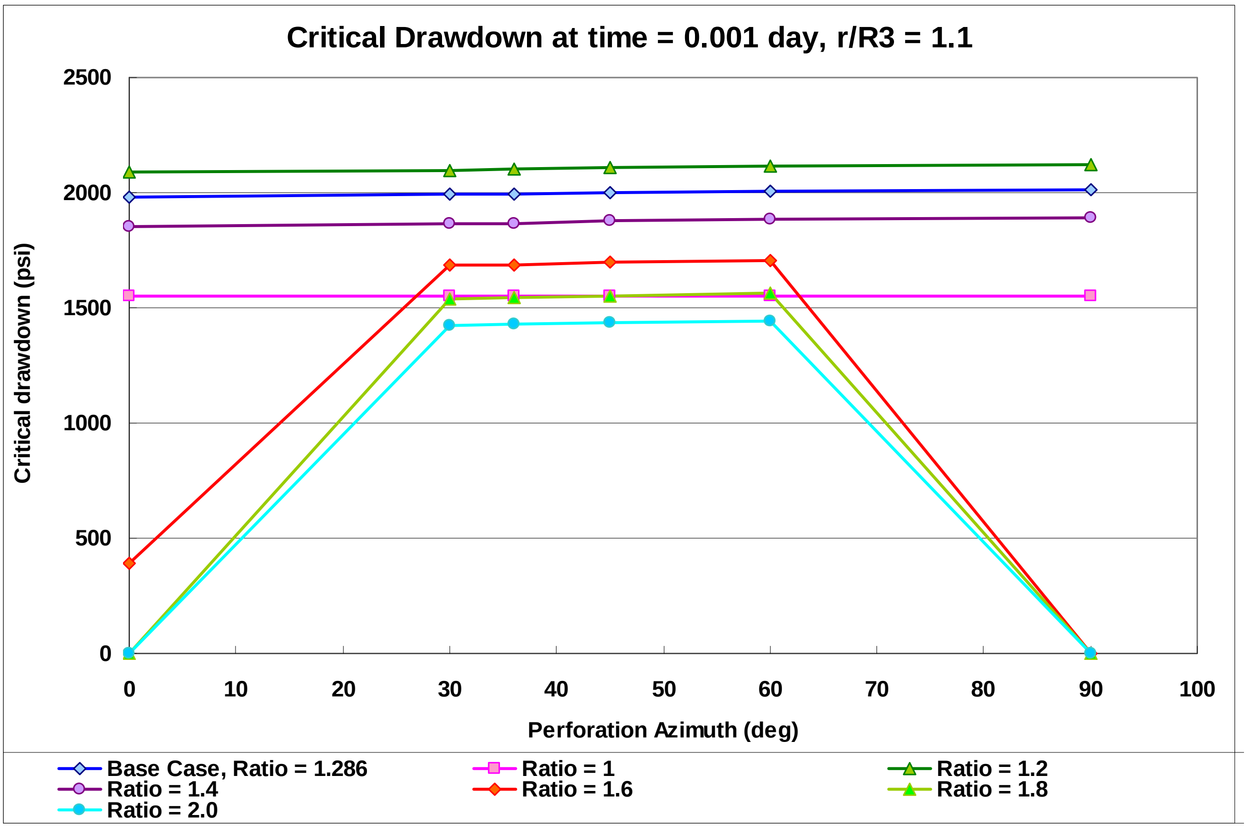

Figure 4.46: Critical drawdown for Case 4–9 compared to Base Case, time = 0.001 day

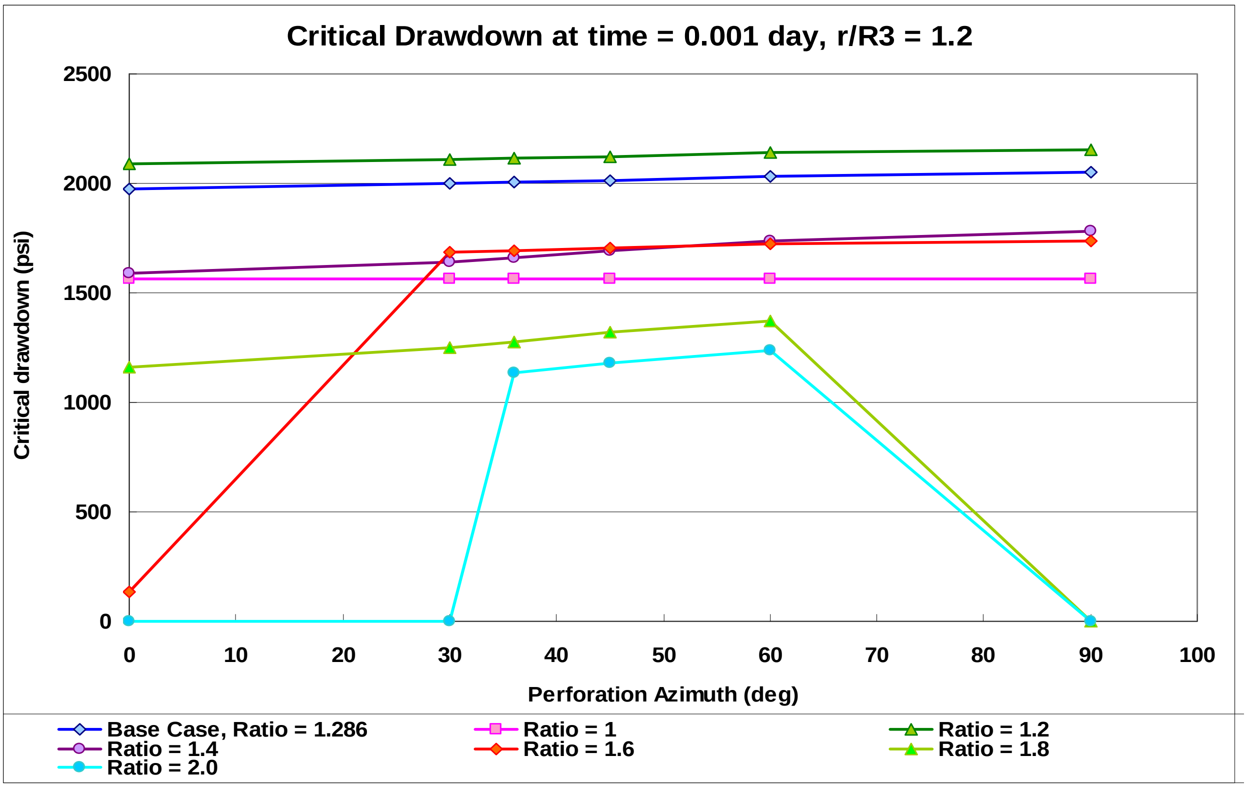

Figure 4.47: Critical drawdown for Case 4–9 compared to Base Case, time = 0.001 day

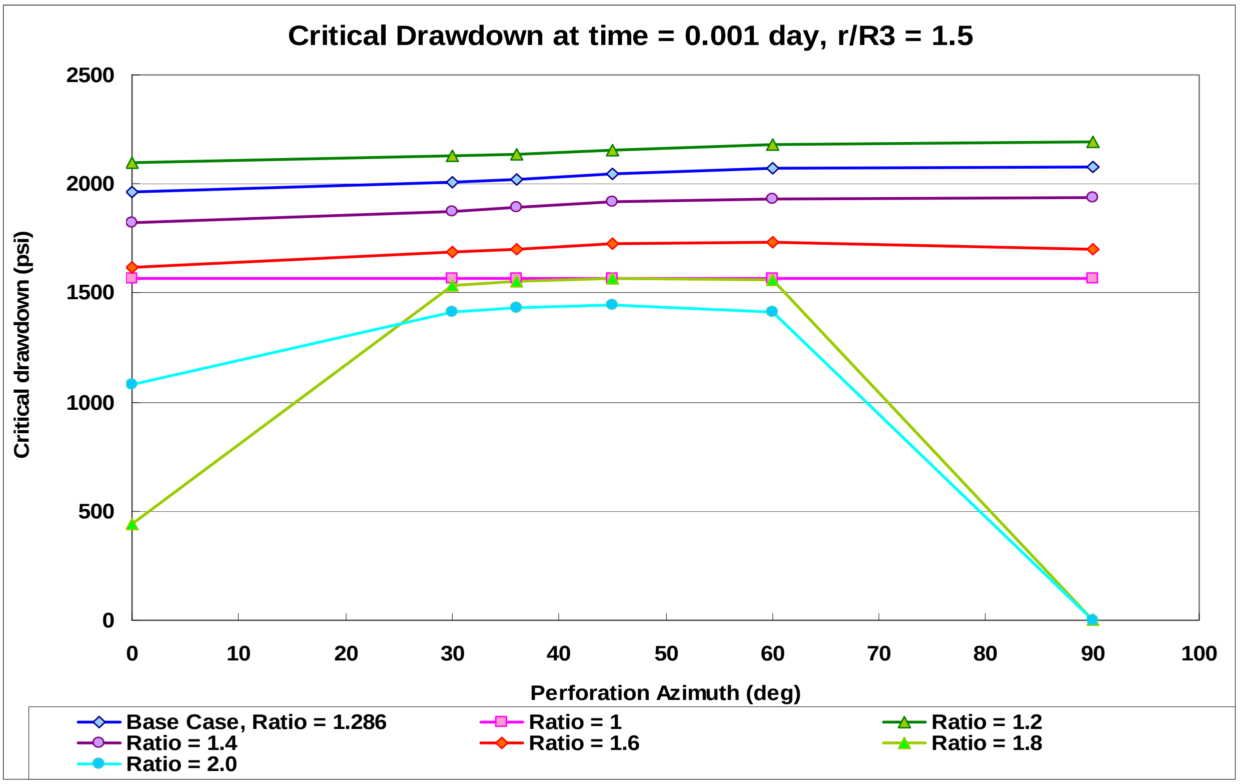

Figure 4.48: Critical drawdown for Case 4–9 compared to Base Case, time = 0.001 day

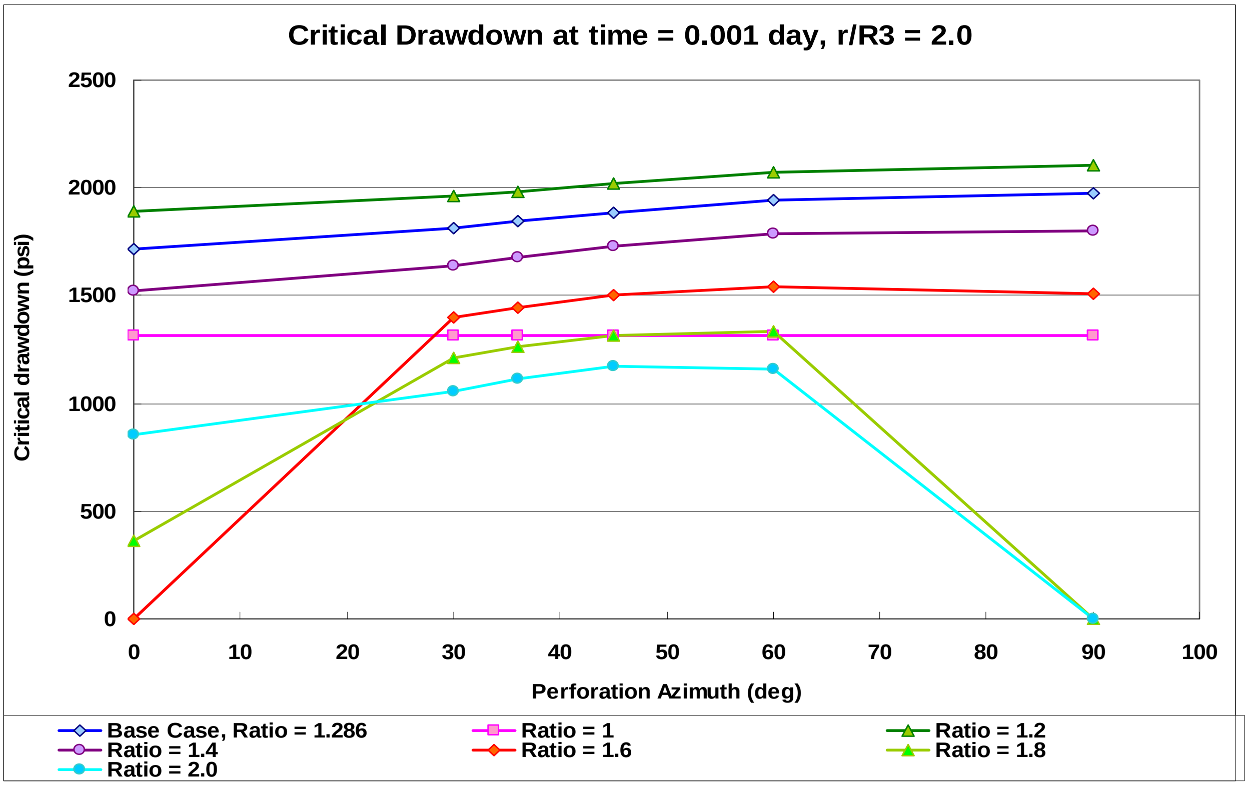

Figure 4.49: Critical drawdown for Case 4–9 compared to Base Case, time = 0.001 day

4.3.3 Significant parameters of critical drawdown pressure based on the sensitivity study

Figures 4.40 and 4.41 indicate that UCS (Unconfined compressive strength) and S_v (Vertical stress) result in a significant impact on the critical drawdown pressure with a low data input range. However, the top five parameters that affect the sand production are UCS, P_o (Initial pore pressure), S_v, perforation azimuth, S_H (Maximum horizontal stress). UCS is one of the default values on the analytical program which allows the user to adjust the number. This study helps the users to be aware of any data input before running the program.

4.3.4 Program discussion.

The goal of this analytical program is to provide a user-friendly version for critical drawdown pressure calculation. The analytical model was modified from a program generated by Hyunil [1]. In this version, several data inputs fill in each parameter. Data input can be imported from outside and all data entries can be stored in the program for future use. In this application, several entries can be made for many parameters simultaneously.

This application is run on MATLAB, but does not require much knowledge of MATLAB functions. Though multiple entries are allowed in this program, the user must be aware of file collapse because waiting for the results is time consuming. The alternative is to run the program from one parameter with multiple values and save the results before running the next parameter when data sensitivity is required. With this option, the file will not collapse and time will not be wasted to fix the problem.

Chapter 5
Conclusions and Future Research

5.1 Conclusions

Perforations are the key to producing the hydrocarbon from reservoirs. However, sand production can be the consequence of poor perforation design. Results of the study on sand production prediction by using a critical drawdown pressure calculation tool are presented. A perforation inclination at 90° is the best alternative providing the highest critical drawdown for maximum sand-free production. This result concurs with the study of Martin et al. [19], and perforation in the direction of σ_h coincides with Hyunil's [1] findings. This direction is suggested when the field can facilitate some sand production near the wellbore. However, neither perforation in the direction of σ_H nor σ_h are recommended when the ratio between maximum and minimum horizontal stresses is greater than 1.4. Shear failure easily occurs when the formation has significant difference between the two horizontal stresses [18]. As a result, a perforation azimuth of 45° and 60 ° should be selected to allow the maximum critical drawdown without sand production.

The application used to calculate the critical drawdown pressure is developed from the code in the MATLAB generated by Hyunil [1]. This new version allows users to simulate the critical drawdown pressure with multiple entries. Hence, this program is not only useful to estimate critical drawdown pressure, but it also provides a sensitivity analysis of each parameter associated with the calculation. This study found that the most significant parameters in the calculation are unconfined compressive stress, initial pore pressure, vertical stress, perforation azimuth, and maximum horizontal stress. In fact, these parameters can be operated when simulating the program to estimate the maximum critical drawdown pressure which allows sandfree production. However, only the perforation azimuth can be easily controlled when completing the well in contrast to the other parameters; namely, the properties of reservoir and casing material. Hence, the perforation azimuth is the most important controlled factor.

5.2 Future work and recommendation

The current study covers wellbore inclination, perforation inclination, ratio between maximum and minimum horizontal stresses, and parameter sensitivity analysis. Because a few wellbore inclinations need to be investigated. Although the sensitivity analysis provides excellent guidance on developing the data input ranges in useful, the range of each parameter should be extended in order to validate the work.

In addition to the findings on critical drawdown pressure, the MATBAL application is definitely useful for critical drawdown calculations, which is time consuming. Future tasks include estimating the sand production rates, making comparisons between the cases studied and revising the critical drawdown calculation code.

Bibliography

[1] Hyunil Jo, Ph.D., Mechanical Behavior of Concentric and Eccentric Casing, Cement, and Formation Using Analytical and Numerical Methods. The University of Texas At Austin, Dissertation Report, 2008.

[2] D. Antheunis, P.B. Vriezen, and B.A. Schipper. Perforation collapse: Failure of perforated friable sandstones. SPE European Spring Meeting, Amsterdam, Netherlands, SPE 5750-MS, 1976.

[3] Rolf K. Bratli and Rasmus Risnes. Stability and Failure of Sand Arches. SPE, 8427-PA, 1981.

[4] M.E. Chenevert and T.W. Thompson. Perforation Stability in Low-Permeability Gas Reservoirs. SPE/DOE Low Permeability Gas Reservoirs Symposium, Denver, Colorado, (13902-MS), 1985.

[5] J.M. Peden and A.A.M. Yassin. The Determination of Optimum Completion and Production Conditions for Sand-Free Oil Production. SPE, (15406-MS), 5-8 October 1986.

[6] Seehong Ong, Baker Atlas and Rico Ramos, Arco Exploration & Production Technology, and Ziqiong Zheng, Baker Atlas. Sand production Prediction in High-Rate, Perforated and Open-Hole Gas Wells.

[7] L. Cui, Y. Abousleiman, A. H.-D. Cheng, and J.-C. Roegiers. Time dependent failure analysis of inclined boreholes in fluid-saturated formations. Journal of Energy Resources Technology (American Society of Mechanical Engineers), 121(1):31-39, 1999.

[8] L. Cui, A.H.-D. Cheng, and Y. Abousleiman. Poroelastic solution for an inclined borehole. Journal of Applied Mechanics, ASME, 64(1):32-38, 1997.

[9] L. Cui, S. Ekbote, and Y. Abousleiman. Effect of pore fluid conditions at the borehole wall on borehole stability, in rock mechanics for industry. In Kranz-R.L. Scott G.A. Amadei, B. and P.H. Smeallie, editors, 37th U.S. rock mechanics symposium proceeding, volume 1, pages 187-194, A.A. Balkema, Rotterdam, 1999.

[10] L. Cui, Ekbote, Y. Abousleiman, M. M. Zaman, and J. C. Roegiers. Borehole stability analyses in fluid saturated formations with impermeable walls. International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts, 36:582-583, 1996. doi:10.1016/S0148- 9062(98)00077-1.

[11] Nicolas Kessler, Yarlong Wang, and F.J. Santarelli. A simplified pseudo 3D model to evaluate sand production risk in deviated Cased holes. SPE, (26541-MS), 3-6 October 1993.

[12] E. Detournay and C. Fairhurst. Two-dimensional elastoplastic analysis of a long, cylindrical cavity and non-hydrostatic loading. International Journal of Rock Mechanics and Mining Science & Geomechanics Abstracts, 24(4): 197-211, 1987.

[13] E. Detournay and Christopher M. St. John. Design charts for a deep circular tunnel under non-uniform loading. Rock Mechanics and Rock Engineering, 21(2): 119-137, 1988. 10.1007/BF01043117.

[14] N. Morita, D.L. Whitfill, O.P. Fedde, and T.H. Levik. Parametric study of sand-production prediction: Analytical approach. SPE Production Engineering, 5(1): 25-33, 1989.

[15] Johan Tronvoll, SPE, SINTEF Petroleum Research, Arne Eek, SPE, Pertra AS, Idar Larsen, SPE, SINTEF Petroleum Research, Francesco Sanfilippo, SPE, Oilfield Geomechanics International. The effect of oriented perforations as a sand-control method: A field Case study from the Varg field, North Sea. SPE 86470, 2004.

[16] J. Zhang and W.B. Standifird, Knowledge Systems, Inc., and X. Shen, Shengang U. of Technology. Optimized perforation tunney geometry, density, and orientation to control sand production. SPE 107785, 2007.

[17] Andrew Acock, Tom ORourke, Daniel Shirmboh, Aberdeen Scottland; Joe Alexander, Abu Dhabi United Arab Emirates; Greg Anderson, Unocal; Toshinobu Kaneko, Adi Venkitaraman, Houston Texas; Jorge Lopez-de-Cardenas, Rosharon Texas; Masatoshi Nishi, Isalamabad Pakistan; Masaaki Numasawa, Katsuhei Yoshioka, JAPEX Tokyo Japan; Alistair Roy, Allan Wilson, BP Aberdeen; Allan Twynam, BP Sunbury England. Practical Approach to Sand Management, page 8/12, source: http://www.slb.com/media/services/resources/oilfieldreview/ors04/spr04/02_sand_management.pdf

[18] Suping Peng, Jitong Fu, Jincai Zhang. Borehole casing failure analysis in unconsolidated formation: A Case study. Journal of Petroleum Science and Engineering, April 2007.

[19] Martin Brudy, Wouter van der Zee, Chritian Bucker. Prediction of optimal perforation orientation and maximum sand-free drawdown using a finite element approach. Source: http://www.geomi.com/AboutUs/publications/sand2.pdf

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