การหาค่าสกินของหลุมแนวนอนที่เจาะผ่านพื้นที่บางส่วนของแหล่งกักเก็บ

นางสาว ธนิฐา วงศ์สวัสดิ์

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DETERMINATION OF PARTIAL PENETRATION SKIN OF HORIZONTAL WELL

Miss Thanitha Wongsawat

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สมการวิเคราะห์จำนวนมากได้ถูกพัฒนาเพื่อใช้ทำนายความสัมพันธ์ของประสิทธิภาพในการไหลเข้าสำหรับหลุมแนวนอน อย่างไรก็ดีหลุมแนวนอนไม่ได้ทะลุผ่านตลอดความยาวของแหล่งกักเก็บเสมอไป เมื่อหลุมเจาะผ่านเฉพาะบางส่วนของแหล่งเก็บและทำให้เกิดความจำกัดในการไหลขึ้นก่อให้เกิดการสูญเสียความดัน ความดันที่ตกลงนี้เป็นที่รู้จักกันในชื่อสกินของการทะลุผ่านบางส่วน มีสมการแบบวิเคราะห์สามสมการที่ใช้สำหรับคำนวณความสามารถในการผลิตของหลุมแนวนอนในการไหลแบบสถานะเดียว คือ (1) Joshi *et al.* (2) Babu กับ Odeh และ (3) Goode กับ Kuchuk ความแตกต่างระหว่างสามวิธีคือวิธีการแก้ไขปัญหาทางคณิตศาสตร์และเงื่อนไขที่ใช้ เครื่องมืออีกชนิดที่ใช้ในการหาความสามารถในการผลิตคือการใช้โปรแกรม PROSPER ซึ่งมีสองวิธีได้แก่ วิธีของ Babu กับ Odeh และ วิธีของ Goode กับ Kuchuk ในการศึกษานี้มีจุดมุ่งหมายในการหาค่าสกินเนื่องจากการทะลุผ่านบางส่วนโดยใช้การจำลองแหล่งกักเก็บเพื่อใช้เปรียบเทียบกับค่าที่ได้จากสมการวิเคราะห์ภายใต้สภาวะของหลุมและแหล่งกักเก็บที่แตกต่างกัน

ผลจากการศึกษาโปรแกรมจำลองแหล่งกักเก็บ (ECLIPSE100) บ่งชี้ว่าตัวแปรหลักสามตัวที่มีผลต่อค่าสกินได้แก่ความยาวของหลุม, ความหนาของแหล่งกักเก็บและแอนไอโซโทรปีของแหล่งกักเก็บ วิธีที่มีความแม่นยำมากที่สุดที่ใช้หาค่าสกินเนื่องจากการทะลุผ่านบางส่วนคือสมการอย่างง่ายของ Goode กับ Kuchuk เมื่อเปรียบเทียบกับค่าสกินที่ได้จากโปรแกรม ECLIPSE100 และวิธีที่แม่นยำน้อยที่สุดคือวิธีของ Goode กับ Kuchuk ที่มีอยู่ในโปรแกรม PROSPER

ภาควิชา..... วิศวกรรมเหมืองแร่และปิโตรเลียม ลายมือชื่อนิสิต..

สาขาวิชา.... วิศวกรรมปิโตรเลียม................ ลายมือชื่อ อ.ที่ปรึกษาวิทยานิพนธ์..........................

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4971610421 : MAJOR PETROLEUM ENGINEERING

KEYWORDS: SKIN FACTOR/ PARTIAL PENETRATION/ HORIZONTAL WELL/ DEVIATED WELL/ SLANT WELL/ LIMITED ENTRY

THANITHA WONGSAWAT: DETERMINATION OF PARTIAL PENETRATION SKIN OF HORIZONTAL WELL. THESIS ADVISOR: ASST. PROF. SUWAT ATHICHANAGORN, Ph.D., 128 pp.

Several analytical solutions have been developed for predicting the inflow performance relationship (IPR) for horizontal wells. However, the horizontal well does not always fully penetrate across the reservoir. When it penetrates only a part of the reservoir, it causes some degree of flow restriction, creating extra pressure loss. This additional pressure drop is known as skin of partial penetration or limited entry, s_{pp}. The pseudo steady state solutions have been presented for determining the partial penetration skin. Three simplified equations namely, (1) Joshi *et al.*, (2) Babu & Odeh, and (3) Goode & Kuchuk, are available for calculating the productivities of the horizontal wells for single-phase flow. The differences between the three methods are their mathematical and the boundary conditions used. Another tool to determine the productivities is using PROSPER. There are two methods available: Babu & Odeh and Goode & Kuchuk. The pressure drop caused by partial penetration obtained from the software can be use to compute partial penetration skin. This study aims to determine skin factor due to partial penetration using the reservoir simulation in order to compare with the values determined from these analytical equations under different well and reservoir conditions. The simulation results indicate that three main parameters affecting the skin factor are length of well, thickness and anisotropy of the reservoir. The most accurate method for determining partial penetration skin factor is Goode & Kuchuk analytical equation compared with the skin factor obtained from Eclipse100 and the least is Goode & Kuchuk available in PROSPER.

Department: Mining and Petroleum Engineering Student's Signature: Thanitha Wongsawat

Field of Study: Petroleum Engineering Advisor's Signature: Suwat Athichanagorn

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LIST OF ABBREVIATIONS

BOPD	barrel oil per day
cp	centipoises
IPR	inflow performance relation
LGR	local grid refinement
md	millidarcy
MSCF	a thousand standard cubic feet
PSI	pound per square inch
PVT	pressure-volume-temperature
RB/D	reservoir barrel per day
RF	recovery factor
SCAL	special core analysis
STB	stock tank barrel
STB/D	stock tank barrel per day
TVD	true vertical depth

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NOMENCLATURE

ENGLISH

A	drainage area
B_o	formation volume factor
b	fractional penetration
C_A	shape factor for a horizontal well
C_f	shape factor for a fractured vertical well
C_H	shape factor
D	turbulence coefficient
D_d	damaged zone high-velocity flow
D_{dp}	high-velocity flow term in the damaged zone immediately surrounding the perforations
D_G	high-velocity flow term in a gravel-packed perforation
D_{res}	reservoir high-velocity flow
D_x	x- dimensions of the grid block
D_y	y- dimensions of the grid block
D_z	z- dimensions of the grid block
h	reservoir thickness
h_D	dimensionless pay thickness
h_p	limited interval open to flow
H_{wj}	well bore pressure head between the connection and the well's bottom hole datum depth
k	permeability
k_h	horizontal permeability
k_v	vertical permeability
k_x	permeability in x-direction
k_y	permeability in y-direction
k_z	permeability in z-direction
L	well length

L_D	dimensionless length
L_x	the length of the deviated well projecting on the X-axis
M_{pj}	phase mobility at the connection
N	sections of open interval
P_j	nodal pressure in the grid block containing the connection
p_R	reservoir pressure
p_w	bottom hole pressure of the well.
p_{wf}	bottom hole well flowing pressure
Δp_{pp}	extra pressure drop caused by partial penetration
Δp_s	pressure drop across the skin zone
$\Delta p_{w,fp}$	pressure drop from fully penetrating horizontal well
$\Delta p_{w,pp}$	pressure drop from partial penetrating horizontal well
q_o	oil rate
$q_{p,j}$	volumetric flow rate of phase in connection at stock tank conditions
q_{Sc}	oil rate at standard condition
r_e	drainage radius
r_o	pressure equivalent radius
r_w	wellbore radius
s	skin factor
s_A	outer boundary geometry skin
s_b	blockage skin
$s_{CA,h}$	shape-related skin factor
s_d	damage skin factor
s_f	skin factor of an infinite-conductivity, fully penetrating fracture
s_G	gravel-pack skin
s_m	mechanical skin factor
s_p	perforation skin
s_{pp}	partial penetration skin factor
s_t	total skin factor
S_w	*water* saturation
S_{wc}	connate water saturation
s_θ	skin due to deviation

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T_{wj} connection transmissibility factor

x_e half the side of drainage area which is parallel to the horizontal well

x_w the distance from the horizontal well mid-point to the closet boundary in the x direction

y_e half the side of drainage area which is perpendicular to the horizontal well

y_w the distance from the horizontal well to the closet boundary in the y direction

z_w vertical distance between the horizontal well and the bottom boundary

GREEK LETTERS

θ angle

ϕ porosity

μ_o oil viscosity

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CHAPTER I

INTRODUCTIONS

Recent advances in drilling and completion has resulted in a rapid increase in the number of horizontal well drilled each year around the world. The major purpose of a horizontal well is to enhance reservoir contact and thereby enhance well productivity. As an injection well, a long horizontal well provides a large contact area and therefore enhances well injectivity, which is highly desirable for enhanced oil recovery (EOR) application.

In general, a horizontal well is drilled parallel to the reservoir bedding plane while a vertical well intersects the reservoir bedding plane at 90°. A typical horizontal well project is different from a vertical well project because productivity of a well depends upon the well length. Moreover, the well length depends on the drilling technique that is used to drill the well. Then, it is essential that reservoir and drilling engineers work together to choose the appropriate drilling technique which will give the desired horizontal well length.

The horizontal well length usually varies from 1000 to 5000 ft. Therefore, horizontal well does not always fully penetrate across the reservoir. In some cases, it can penetrate only a part of the reservoir and cause some degree of flow restriction, creating extra pressure loss. This additional pressure drop is known as skin of partial penetration or limited entry, s_{pp}. Generally, we are interested only in the pseudosteady-state condition, and neglect the transient of the skin effect. It is often useful to estimate the size of the partial penetration skin factor, since it can be subtracted from the apparent skin to determine whether the well is actually damaged.

Actually, most wells do not penetrate the producing formation perpendicularly. Instead, there is a certain angle between the normal to the formation plane and the well axis, such as when a vertical well penetrates a dipping formation or when a directionally drilled well penetrates a horizontal formation. These kinds of wells are called "slanted or deviated well".

As horizontal and deviated well technology have developed, many analytical equations for determining inflow performance and its skin factors have been proposed based on different assumptions. It is often useful to estimate the size of the partial penetration skin factor, since it can be subtracted from the apparent skin to determine whether the well is actually damaged. This study aims to determine skin factor due to partial penetration for both horizontal and deviated well using reservoir simulation and compare it with values determined by various methods under different well and reservoir conditions. The skins calculated from the study can then be used to evaluate performance of horizontal wells drilled in various ranges of wellbore, reservoir, and fluid conditions.

1.1 Outline of Methodology

ECLIPSE100 reservoir simulation software is used to simulate and match the history pressure drop of the well. The following shows the procedure for this study:

1. Build the reservoir model with a partial penetrating well.
2. Build the same reservoir model with the fully penetrating well model.
3. Compare pressure histories obtained from the two reservoir models.
4. Adjust the skin factor into the fully penetrating well model.
5. Repeat step 3 and 4 until the pressure histories are matched.
6. Change the factor such as well length, wellbore diameter, and fluid properties.
7. Determine the skin factor from different scenarios.
8. Obtain the skin factor from each scenario and compared to the various methods.

1.2 Thesis Outline

This thesis consists of 6 chapters as outlined below:

Chapter 1 introduces the main idea and concepts of this work

Chapter 2 reviews previous studies on partial penetration skin for horizontal and deviated wells.

Chapter 3 describes the basic principles of basic principles and theories used in application of equations, well performance software program (PROSPER) and reservoir simulation (ECLIPSE 100) for determination of partial penetration skin factor for horizontal and deviated wells.

Chapter 4 studies the effect pressure due to partial penetration on horizontal and deviated well.

Chapter 5 concludes the results obtained from the study.

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CHAPTER II

LITERATURE REVIEW

Since the beginning of petroleum production, wells have been drilled and completed through only a fraction of the total formation to avoid contact with the water zone that may underline the oil or the gas zone or perhaps because of difficulties in controlling mud circulation in the pay zone.

A completion arrangement where only limited pay-zone interval is open to production is referred to as partial penetration or limited entry. Numerous cases of partial penetration are mentioned and discussed in the petroleum literature. Some related works are reviewed in this chapter.

Brons and Marting [1] studied the productivity of the vertical wells and suggested that the effect of partial penetration and limited entry can be expressed as a skin factor. The study dealt with different kinds of the impairment in productivity caused by a skin. The authors considered a well in which part of the productive formation is blocked off completely, either by incomplete penetration or by exclusion of parts of the productive zone by blank casing. They solved the productivity analytical formulation using numerical integration and provided a table of values for a function of the fractional penetration, $G(b)$. They concluded that better productivity is obtained from an interval open in the middle of a productive zone than from the same open interval located at either top or bottom of the zone. Additionally, the larger the number of intervals for a given total penetration ratio, the higher the productivity will be.

As the horizontal wells have been increasingly used in field application, pressure transient solutions for horizontal wells in the finite and infinite reservoirs have been discussed. Mutalik, Godbole, and Joshi [2] presented a pseudo-steady flow equation to forecast the production from horizontal wells in rectangular drainage areas. The equation was developed from the solution for a fully penetrating infinite conductivity vertical fracture and is applicable for wells located either centrally or off-centrally in the areal plane. Analytical pressure transient solutions were used to calculate the shape factor, $C_{A,h}$ and the corresponding equivalent skin factor, $s_{CA,h}$. The use of this equivalent pseudo-skin factor provides a method to predict the inflow performance relationship curve for horizontal wells. The results showed that the horizontal well pressure response asymptotically approaches that of fully penetrating, infinite-conductivity vertical fracture at very large values of dimensionless well length, L_D for centered as well as off-centered wells in a rectangular drainage area. They concluded that the performance of a horizontal well can be predicted from that of a fully penetrating, infinite-conductivity vertical fracture.

Babu and Odeh [(3)] presented an equation for pseudosteady-state flow for a horizontal well that is easy to use and has an identical form to the well-known productivity equation for a vertical well. Application of the equation requires determination of two parameters (1) a geometric factor that accounts for the effect of permeability anisotropy, well location, and the relative dimensions of the drainage volume and (2) the skin caused by restricted entry, which accounts for the effect of the well length. The solution to the partial-differential equation for a finite reservoir that describes the flow behavior of a horizontal well and that preserves the physics is very complex. The authors reduced the complex solution to a simplified equation for calculating productivity with requirement that the drainage volume is approximately box-shaped. Because the simple equation was derived from complicated expressions, it is not exact. In most cases where the well penetration is ≥50%, the error in the productivity calculation is less than 3%. The error may increase to 10% as penetration decreases.

Goode and Kuchuk [(4)] presented formulas for evaluating inflow performance of a horizontal well in a rectangular drainage region bounded above and below. The upper boundary may be either sealed to flow (no flow) or at constant pressure (e.g., gas cap). The well can be placed anywhere within drainage volume and be of any length. The inflow-performance formulas for horizontal wells presented make certain limiting assumptions about the well relative to the size of the drainage region, the formation thickness, and the well location. For no-flow boundary, if the well is not long compared with the scaled reservoir thickness, the distance from the well to any lateral boundary must be large relative to the distance from the well to the top and bottom boundary. The authors also provided a simple equation for calculating the inflow performance of a short well (compared to the drainage area). They concluded that, these new inflow performance formulas for horizontal wells with and without a constant-pressure boundary can be applied to horizontal wells of arbitrary length producing from a closed rectangular region of arbitrary aspect ratio where the well is placed at any location within the region.

Actually, most wells do not penetrate the producing formation perpendicularly. Instead, there is a certain angle between the normal to the formation plane and the well axis, such as when a vertical well penetrates a dipping formation or when a directionally drilled well penetrates a horizontal formation. Roemershuser and Hawkins[5], studied steady state flow in a reservoir producing through a fully penetrating slanted well by using an electrical model. They considered a circular reservoir of finite extent and concluded that the slant of fully penetrating well causes an increase in the well productivity compared with a vertical well. The increase in well productivity results from the decrease in the resistance to flow around the wellbore due to the increase in the producing interval area exposed to flow. This increase in well productivity indicates that a fully penetrating slanted well creates a negative skin effect.

Cinco-Ley, Ramey and Miller [6] studied unsteady-state performance of slanted well. They presented analytical solution for dimensionless pressure distribution created by a fully penetrating, directionally drilled well. And they also calculated pseudo-skin factors due to slanted wells. They concluded that the slant of a fully penetrating well creates a negative skin effect that is a function of angle of slant and formation thickness.

Besson [7] provided a method to estimate the productivity of well with respect to any angle of slant and anisotropy of permeability. The well pressure decline curves were generated by a semi-analytical in-house simulator. These led to a geometrical pseudo-skin factor which was matched for slanted wells with an analytically-derived equation. An unrestrictive approach of anisotropy is possible through a spatial transformation from real medium into equivalent isotropic medium. The equation of the pseudo skin factor is modified according to this transformation. The study show that the performance of the horizontal and slanted wells can be studied through the definition of a geometrical pseudo-skin factor, long-time performance is the same as for a fully penetrating vertical well with a wellbore skin factor.

Economides and Rogers (8) presented comprehensive correlations for quick calculation of mechanical skin effect due to slant, based on dimensionless reservoir thickness, deviation angle, and index of anisotropy. They compared the results of calculated mechanical skin effect to Cinco *et al.* (6) results. The results suggested that the previous assumption of isotropy would greatly overestimate the absolute magnitude of the skin.

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CHAPTER III

THEORIES AND CONCEPTS

This chapter presents the basic principles and theories used in application of equations, well performance software program (PROSPER) and reservoir simulation (ECLIPSE 100) for determination of partial penetration skin factor for horizontal and deviated wells. First, the basic concepts concerning with vertical, horizontal and deviated wells are introduced. The fundamental concepts of skin are introduced; then, concept of the partial penetration skin for vertical, horizontal and deviated wells are described. Each method used in this study is described.

3.1 Well Inflow Performance

This Skin factor has a significant affect on reservoir inflow performance. The concept of well inflow performance is introduced in this section. Three types of inflow performance which are inflow performances for the vertical and the horizontal wells, and the inflow performance calculation used in ECIPSE 100 are described.

3.1.1 Vertical Well Inflow Performance

Vertical well is the basic well orientation used to study the inflow performance. The equation describing the behavior of its inflow performance is based on Darcy's law. The inflow equation for pseudo-steady state flow is

$$q_o = \frac{kh(p_R - p_{wf})}{141.2\mu_o B_o[\ln(r_e/r_w) - 0.75 + s]} \quad (3.1)$$

where

q_o	=	oil rate, STB/day
k	=	permeability, md
h	=	reservoir thickness, ft
p_R	=	reservoir pressure, psi
p_{wf}	=	bottom hole well flowing pressure, psi
μ_o	=	viscosity, cp
B_o	=	formation volume factor, RB/STB
r_e	=	drainage radius, ft
r_w	=	wellbore radius, ft
s	=	skin factor, dimensionless

3.1.2 Horizontal Well Inflow Performance

The inflow performance of the horizontal well was explained by several studies. There are three simplified equations available for calculate pseudo-steady state productivities of horizontal wells accounting partial penetration skin for single-phase flow. These equations were introduced by (1) Joshi, (2) Babu & Odeh and (3) Goode & Kuchuk. In these methods, the reservoir is assumed to be bounded in all directions and the horizontal well is located in the rectangular bounded drainage area. A fluid of slight but constant compressibility is produced through the horizontal well. The fluid properties are assumed to be independent of pressure, and gravity effects are neglected. It is also assumed that the length of the horizontal wellbore is much larger than the thickness of the formation. The pressure in the reservoir prior to producing the well is uniform and equal to p_i. The well is produced at a constant rate q.

Figure 3.1 illustrates the horizontal well configuration associated with the analytical solution.

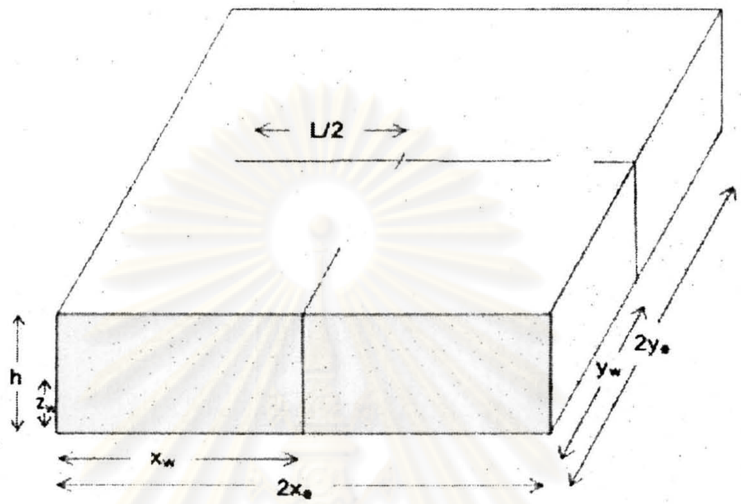

Figure 3.1: Horizontal well configuration. [4]

x_e = half the side of drainage area which is parallel to the horizontal well

y_e = half the side of drainage area which is perpendicular to the horizontal well

x_w = the distance from the horizontal well mid-point to the closet boundary in the x direction

y_w = the distance from the horizontal well to the closet boundary in the y direction

z_w = vertical distance between the horizontal well and the bottom boundary

L = well length, ft

3.1.2.1 Joshi *et al.* [2]

For rectangular drainage areas with $2x_e/(2y_e) = 1$ to 20, Joshi *et al*. reported the shape factors and the corresponding equivalent skin factor $s_{CA,h}$ for horizontal well located at various positions within the drainage volume. The skin factors $s_{CA,h}$ for centrally located wells within drainage area with ratios of sides, $2x_e/(2y_e) = 1$, 2 and 5 are plotted in Figures 3.2 through 3.4 and are summarized in Table 3.1.

The following equation can be used to calculate the inflow performance of a horizontal well:

$$q = \frac{0.007078kh\,(p_R - p_{wf})/(\mu_o B_o)}{\ln\left(\frac{r_e'}{r_w}\right) - A' + s_f + s_m + s_{CA,h} - C' + Dq} \tag{3.2}$$

where

D = turbulence coefficient, 1/BOPD for oil and 1/MSCF for gas

r_e' = $\sqrt{A/\pi}$

s_m = mechanical skin factor, dimensionless

= $s_d(h/L)\sqrt{k_h/k_v}$

k_h = horizontal permeability, md

= $\sqrt{k_x k_y}$

k_x = permeability in x-direction, md

k_y = permeability in y-direction, md

k_v = vertical permeability, md

s_d = damage skin factor

s_f = skin factor of an infinite-conductivity, fully penetrating fracture of length L

= $-\ln[L/4r_w]$

$s_{CA,h}$ = shape-related skin factor

= $\ln\sqrt{C_{A,ref}/C_A}$

C_A = shape factor for a horizontal well

C_f = shape factor for a fractured vertical well

C' = shape factor conversion constant

= 1.386

L_D = dimensionless length

= $(L/2h)\sqrt{k_h/k_v}$

The constant C' account for the difference in the definitions of shape factor, C_A and C_f. This constant is applicable to all drainage patterns. Furthermore, $A' = 0.750$ and $C_{A,ref} = 31.62$ for circular drainage area and $A' = 0.738$ and $C_{A,ref} = 30.8828$ for a square drainage area. Shape factors for a horizontal well C_A for different fracture penetrations in a square drainage area are listed in Table 3.1.

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Table 3.1: Shape factors, C_A, for horizontal wells with various well penetrations and different rectangular drainage areas. [9]

	$L/(2x_e)$				
L_D	0.2	0.4	0.6	0.8	1
(1) $x_e/y_e = 1$					
1	0.0163	0.0043	0.0034	0.0020	0.00085
5	0.9813	0.7030	0.6268	0.4406	0.27730
10	1.4438	1.1538	1.0241	0.7616	0.50100
20	1.6917	1.4595	1.2644	0.9673	0.65060
50	1.8178	1.6276	1.4020	1.0909	0.74350
100	1.8340	1.6738	1.4390	1.1260	0.77100
(2) $x_e/y_e = 2$					
1	0.0044	0.0033	0.0013	0.00061	0.00025
5	0.5869	0.5440	0.4230	0.30510	0.19000
10	0.9531	0.9095	0.7664	0.58525	0.38100
20	1.1734	1.1359	0.9963	0.78250	0.52120
50	1.2986	1.2682	1.1394	0.91090	0.61450
100	1.3322	1.3046	1.1817	0.95000	0.64380
(3) $x_e/y_e = 5$					
1	0.0002	0.0003	0.00019	0.0003	0.00011
5	0.0859	0.1490	0.18690	0.2111	0.12410
10	0.1606	0.2850	0.38760	0.4144	0.12480
20	0.2120	0.3822	0.54120	0.5609	0.35270
50	0.2442	0.4446	0.64500	0.6571	0.41870
100	0.2503	0.4636	0.67820	0.6870	0.43970

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Shape factors C_f for different fracture penetrations in a square drainage area and a rectangular drainage area are listed in Tables 3.2 and 3.3, respectively. Shape factors for off-centered fractured wells in a rectangular drainage area are given in Tables 3.4 and 3.5.

Table 3.2: Shape factors, C_f, for fractured vertical wells in a square drainage area.[2]

x_f/x_e	Shape factors, C_f
0.1	2.6541
0.2	2.0348
0.3	1.9986
0.5	1.6620
0.7	1.3127
1.0	0.7887

Table 3.3: Shape factors, C_f, for fractured vertical well located centrally in a rectangular drainage area. [2]

	x_e/y_e					
x_f/x_e	1	2	3	5	10	20
0.1	2.020	1.4100	0.751	0.2110	0.0026	0.000005
0.3	1.820	1.3611	0.836	0.2860	0.0205	0.000140
0.5	1.600	1.2890	0.924	0.6050	0.1179	0.010550
0.7	1.320	1.1100	0.880	0.5960	0.3000	0.122600
1.0	0.791	0.6662	0.528	0.3640	0.2010	0.106300

Table 3.4: Shape factors, C_f, for off-centered fractured vertical wells. [2] *(x_w represents the distance of the fracture center from the nearest x boundary)*

	Influence of y_w/y_e *			
		y_w/y_e		
	x_f/x_e	**0.25**	**0.5**	**1.0**
$x_e/y_e = 1$				
	0.1	0.2240	0.8522	2.0200
	0.3	0.2365	0.7880	1.8220
	0.5	0.2401	0.7165	1.6040
	0.7	0.2004	0.5278	1.3170
	1.0	0.1351	0.3606	0.7909
$x_e/y_e = 2$				
	0.1	0.2272	0.7140	1.4100
	0.3	0.3355	0.7700	1.3610
	0.5	0.4325	0.8120	1.2890
	0.7	0.4431	0.7460	1.1105
	1.0	0.2754	0.4499	0.6660
$x_e/y_e = 5$				
	0.1	0.0375	0.09185	0.2110
	0.3	0.1271	0.20320	0.2864
	0.5	0.2758	0.38110	0.4841
	0.7	0.3851	0.49400	0.5960
	1.0	0.2557	0.31120	0.3642

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Table 3.5: Shape factors, C_f, for off-centered fractured vertical wells. [2] *(y_w represents the distance of the fracture center from the nearest y boundary)*

	Influence of y_w/y_e *			
		y_w/y_e		
	x_f/x_e	**0.25**	**0.5**	**1.0**
$x_e/y_e = 1$				
	0.1	0.9694	1.7440	2.0200
	0.3	1.1260	1.7800	1.8200
	0.5	1.2708	1.7800	1.6000
$x_e/y_e = 2$				
	0.1	0.3679	1.0680	1.4098
	0.3	0.5630	1.2980	1.3611
	0.5	0.8451	1.5470	1.2890
$x_e/y_e = 5$				
	0.1	0.0058	0.0828	0.2110
	0.3	0.0317	0.2540	0.2864
	0.5	0.1690	0.7634	0.6050

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Shape-related skin factors for horizontal wells, $s_{CA,h}$ (base upon a square reference area), are tabulated in Table 3.5 and are plotted in Figures 3.2 through 3.4.

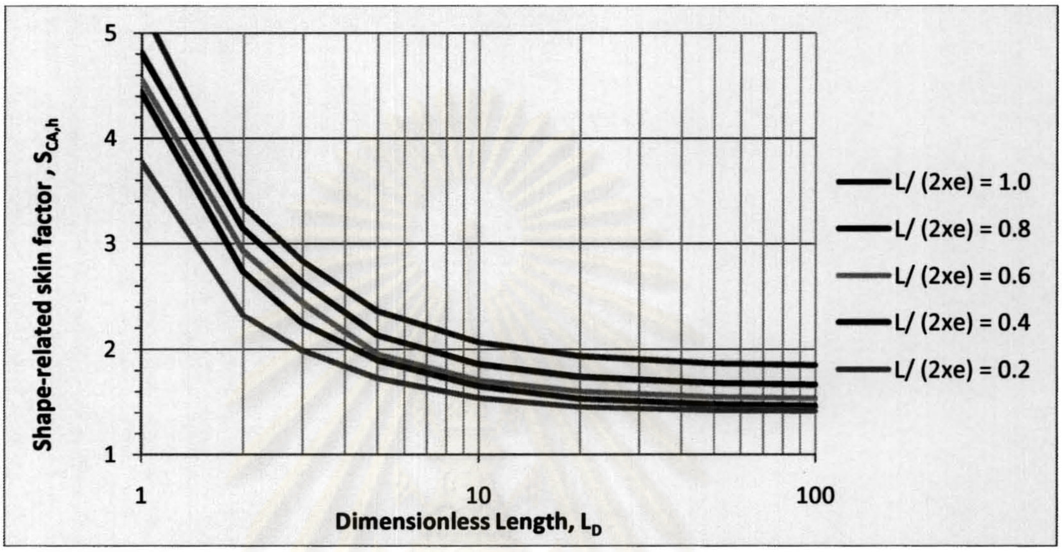

Figure 3.2: Shape related skin factor, $s_{CA,h}$, for a horizontal well in square drainage area $(x_e/y_e) = 1$. [9]

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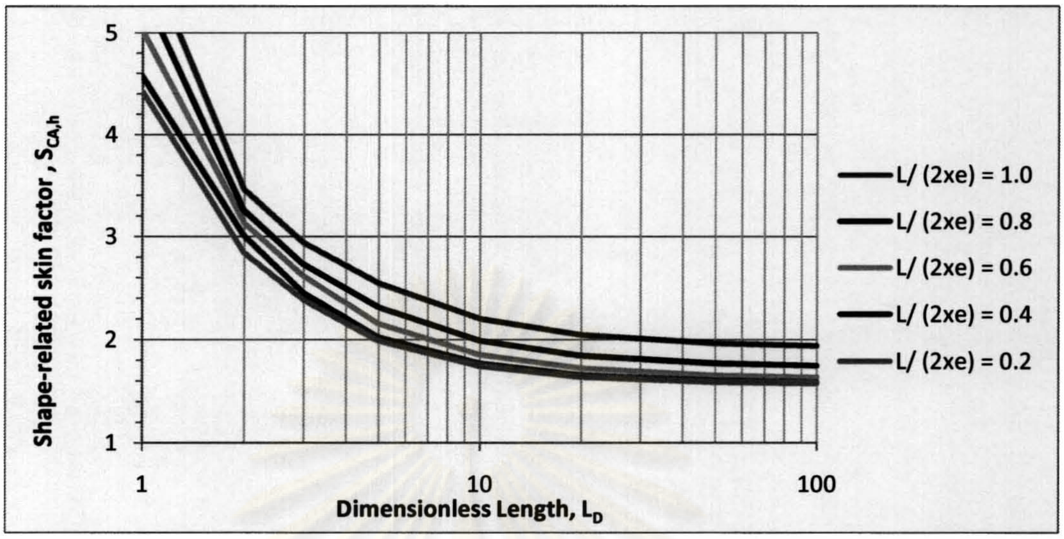

Figure 3.3: Shape related skin factor, $s_{CA,h}$, for a horizontal well in square drainage area $(x_e/y_e) = 2$. [9]

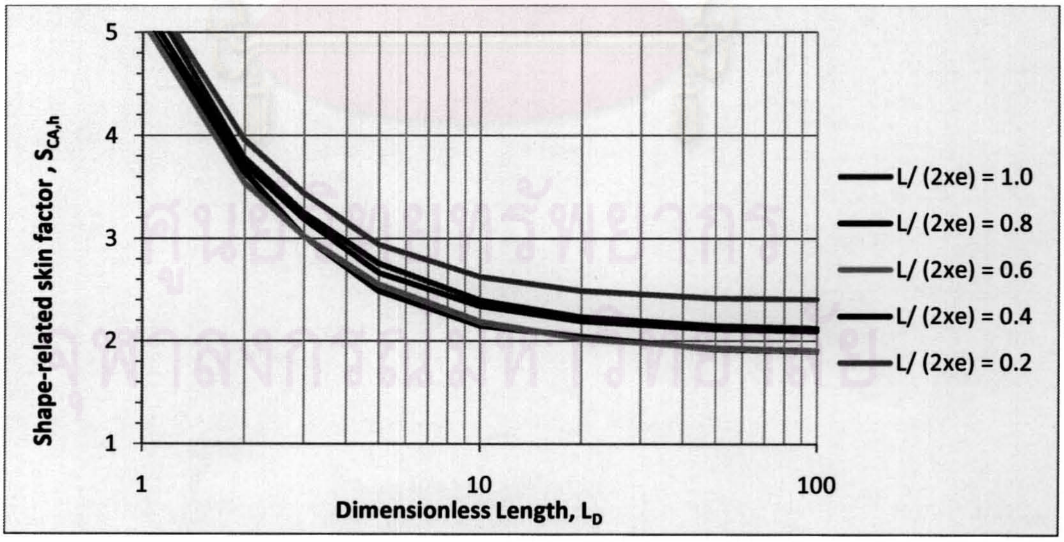

Figure 3.4: Shape related skin factor, $s_{CA,h}$, for a horizontal well in square drainage area $(x_e/y_e) = 5$. [9]

Table 3.5: Shape related skin factors, $s_{CA,h}$, for horizontal wells for various well penetrations and different rectangular drainage areas. [9]

	$L/(2x_e)$				
L_D	0.2	0.4	0.6	0.8	1
(1) $x_e/y_e = 1$					
1	3.772	4.439	4.557	4.819	5.250
2	2.321	2.732	2.927	3.141	3.354
3	1.983	2.240	2.437	2.626	2.832
5	1.724	1.891	1.948	2.125	2.356
10	1.536	1.644	1.703	1.851	2.061
20	1.452	1.526	1.598	1.733	1.930
50	1.420	1.471	1.546	1.672	1.863
100	1.412	1.458	1.533	1.656	1.845
(2) $x_e/y_e = 2$					
1	4.425	4.578	5.025	5.420	5.860
2	2.840	3.010	3.130	3.260	3.460
3	2.380	2.450	2.610	2.730	2.940
5	1.982	2.020	2.150	2.310	2.545
10	1.740	1.763	1.850	1.983	2.198
20	1.635	1.651	1.720	1.839	2.040
50	1.584	1.596	1.650	1.762	1.959
100	1.572	1.582	1.632	1.740	1.935
(3) $x_e/y_e = 5$					
1	5.500	5.270	5.110	5.140	5.440
2	3.960	3.720	3.540	3.650	3.780
3	3.440	3.190	3.020	3.020	3.250
5	2.942	2.667	2.554	2.493	2.758
10	2.629	2.343	2.189	2.155	2.399
20	2.491	2.196	2.022	2.044	2.236
50	2.420	2.120	1.934	1.925	2.150
100	2.408	2.100	1.909	1.903	2.126

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3.1.2.2 Babu & Odeh [3]

In this method, a horizontal well problem is treated as a problem similar to that for a partially penetrating vertical well. If a partially penetrating vertical well is turned sideways, it will result in a partially penetrating horizontal well. Babu & Odeh derived the following equation for horizontal well pseudo-steady state flow.

$$q = \frac{7.08 \times 10^{-3} 2x_e \sqrt{k_y k_v}(p_R - p_{wf})/B_o \mu_o}{\left[\ln(\sqrt{A_1}/r_w) + \ln C_H - 0.75 + s_{pp}\right]} \tag{3.3}$$

Calculation of $\ln C_H$

$$\ln C_H = 6.28 \frac{2y_e}{h} \sqrt{\frac{k_v}{k_y}} \left[\frac{1}{3} - \frac{y_w}{2y_e} + \left(\frac{y_w}{2y_e}\right)^2\right] - \ln\left(\sin \frac{180^\circ z_w}{h}\right) - 0.5 \ln\left[\left(\frac{2y_e}{h}\right)\sqrt{\frac{k_v}{k_y}}\right] - 1.088 \tag{3.4}$$

where

s_{pp} = skin factor due to partial penetration

C_H = shape factor

A_1 = horizontal well drainage area in the vertical plane ($A_1 = 2y_e h$), ft^2

The term s_{pp} accounts for the skin factor due to partial penetration of horizontal well in the areal plane. $s_{pp} = 0$ when $L = 2x_e$.

3.1.2.3 Goode & Kuchuk [4]

Goode & Kuchuk derived the inflow equation based on an approximate infinite-conductivity solution, where constant wellbore pressure is obtained by averaging pressure values of uniform-flux solution along the well length. The derived equation is expressed as

$$q = \frac{7.08 \times 10^{-3} k_h h (p_R - p_{wf}) / \mu_o B_o}{0.5F + \frac{h}{L}\sqrt{\frac{k_h}{k_v}} s_x} \tag{3.5}$$

F is a dimensionless function and depends upon $y_w/(2y_e)$, $x_w/(2x_e)$, $L/(4x_e)$ and $(y_e/x_e)\sqrt{k_x/k_y}$,given in Table 3.2. The value of s_x is calculated using the following equation:

$$s_x = \ln\left[\left(\frac{\pi r_w}{h}\right)\left(1 + \sqrt{\frac{k_v}{k_h}}\right)\sin\left(\frac{\pi z_w}{h}\right)\right] - \sqrt{\frac{k_h}{k_v}}\left(\frac{2h}{L}\right)\left[\frac{1}{3} - \left(\frac{z_w}{h}\right) + \left(\frac{z_w}{h}\right)^2\right] \tag{3.6}$$

It is important to note that equation (3.5) does not have B_o, i.e., the formation volume factor term. Hence, to obtain productivity for surface conditions, the B_o term must be added in the denominator of equation (3.5).

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Table 3.6: Values of dimensionless function, F, for calculation of productivity of horizontal wells (Method: Goode & Kuchuk). [9]

$\frac{y_e}{x_e}\sqrt{\frac{k_x}{k_y}}$	$y_w/(2y_e) = 0.50, x_w/(2x_e) = 0.50$ $L/(4x_e)$				
	0.1	0.2	0.3	0.4	0.5
0.25	3.80	2.11	1.09	0.48	0.26
0.50	3.25	1.87	1.12	0.69	0.52
1.00	3.62	2.30	1.60	1.21	1.05
2.00	4.66	3.34	2.65	2.25	2.09
4.00	6.75	5.44	4.74	4.35	0.19

$\frac{y_e}{x_e}\sqrt{\frac{k_x}{k_y}}$	$y_w/(2y_e) = 0.25, x_w/(2x_e) = 0.25$ $L/(4x_e)$				
	0.1	0.2	0.3	0.4	0.5
0.25	9.08	7.48	6.43	5.65	5.05
0.50	6.97	5.56	4.71	4.12	3.71
1.00	6.91	5.54	4.76	4.24	3.90
2.00	8.38	7.02	6.26	5.76	5.44
4.00	11.97	10.61	9.85	9.36	9.04

$\frac{y_e}{x_e}\sqrt{\frac{k_x}{k_y}}$	$y_w/(2y_e) = 0.25, x_w/(2x_e) = 0.50$ $L/(4x_e)$				
	0.1	0.2	0.3	0.4	0.5
0.25	4.33	2.48	1.36	0.70	0.46
0.50	3.89	2.42	1.58	1.10	0.92
1.00	4.47	3.13	2.41	2.00	1.83
2.00	6.23	4.91	4.22	3.83	3.67
4.00	9.90	8.58	7.88	7.49	7.33

$\frac{y_e}{x_e}\sqrt{\frac{k_x}{k_y}}$	$y_w/(2y_e) = 0.50, x_w/(2x_e) = 0.25$ $L/(4x_e)$				
	0.1	0.2	0.3	0.4	0.5
0.25	8.44	6.94	5.98	5.26	4.70
0.50	6.21	4.83	4.02	3.47	3.08
1.00	5.86	4.50	3.73	3.23	2.90
2.00	6.73	5.38	4.62	4.12	3.81
4.00	8.82	7.46	6.71	6.21	5.89

3.1.3 Deviated/Slant Well Inflow Performance

Deviated holes are drilled to increase the surface area exposed to formation, thereby improving the well productivity. Thin bedded pay zones that are separated by low permeability formation streaks are attractive targets for deviated holes. The equation which is widely used in numerical models as a wellbore equation is expressed as:

$$q = \frac{7.08 \times 10^{-3} kh(p_R - p_{wf})}{B\mu\left(\ln\frac{r_e}{r_w} + s_\theta + s\right)} \tag{3.7}$$

where s_θ is the skin factor due to deviation of wellbore.

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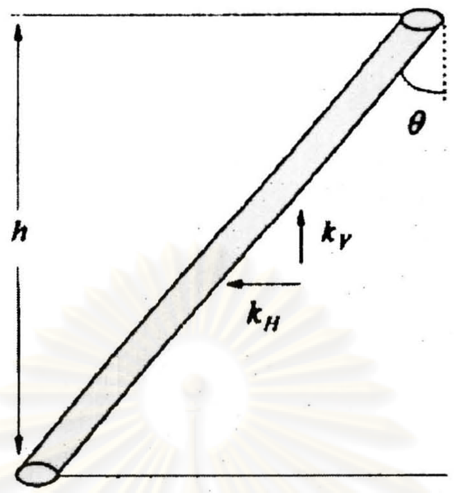

Figure 3.5: Deviated/slant well configuration. [9]

Figure 3.5 illustrates the deviated/slant well configuration associated with the analytical solution.

3.1.4 Inflow Performance in PROSPER Software

PROSPER is Petroleum Experts Limited's advanced PROduction and System PERformance analysis software which is a well performance, design and optimization program which is part of the Integrated Production Modelling Toolkit (IPM). The software can be used to generate inflow performance relationship for horizontal wells. Reservoir fluid properties can be generated using PVT DATA module and the inflow performance relation (IPR) can be generated using IPR DATA module.

There are two horizontal well equations that include the effect of partial penetration available in PROSPER: Babu & Odeh and Goode & Kuchuk. However, these two equations cannot be used for deviated wells.

3.1.5 Inflow Performance in ECLIPSE 100 Reservoir Simulator [10]

In ECLIPSE 100, the inflow performance relationship is written in terms of the volumetric production rate of each phase at stock tank conditions as a function of transmissibility, mobility, and pressure difference around the wellbore.

$$q_{p,j} = T_{wj} M_{pj} \left(P_j - P_w - H_{wj} \right) \tag{3.8}$$

where

$q_{p,j}$ is the volumetric flow rate of phase in connection at stock tank conditions. The flow is taken as positive from the formation into the well and negative from the well into the formation.

T_{wj} is the connection transmissibility factor, defined below.

M_{pj} is the phase mobility at the connection.

P_j is the nodal pressure in the grid block containing the connection.

P_w is the bottom hole pressure of the well.

H_{wj} is the well bore pressure head between the connection and the well's bottom hole datum depth. $P_w + H_{wj}$ is thus the pressure in the well at the connection, which we call the "connection pressure".

The connection transmissibility factor depends on the geometry of the connecting grid block, the well bore radius, and the rock permeability. For Cartesian grid, this factor can be calculated by using the formula:

$$T_{wj} = \frac{c\theta kh}{\ln(r_o/r_w) + s} \tag{3.9}$$

where

c is a unit conversion factor

(0.001127 in field units, 0.008527 in metric units, 3.6 in lab units)

θ is the angle of the segment connecting with the well, in radians. In a Cartesian grid its value is 6.2832 (= 2), as the connection is assumed to be in the center of the grid block

kh is the effective permeability times net thickness of the connection. For a vertical well the permeability used here is the geometric mean of the x- and y-direction permeabilities, $k = \left(k_x k_y\right)^{1/2}$

r_o is the "pressure equivalent radius" of the grid block, defined below

r_w is the well bore radius

s is the skin factor

The pressure equivalent radius of the grid block is defined as the distance from the well at which the local pressure is equal to the nodal average pressure of the block. In a Cartesian grid, we use Peaceman's formula, which is applicable to rectangular grid blocks in which the permeability may be anisotropic. The vertical well is assumed to penetrate the full thickness of the block, through its center, perpendicularly to two of its faces.

$$r_o = 0.28\frac{\left[D_x^2\left(\frac{k_y}{k_x}\right)^{1/2} + D_y^2\left(\frac{k_x}{k_y}\right)^{1/2}\right]^{1/2}}{\left(\frac{k_y}{k_x}\right)^{1/4} + \left(\frac{k_y}{k_x}\right)^{1/4}} \tag{3.10}$$

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where D_x and D_y are the x- and y- dimensions of the grid block, and $k_x$and k_y are the x- and y- direction permeabilities.

In case of horizontal well, the well may penetrate the block in either the x- or y direction. Appropriate components of permeability and block dimensions are substituted in equation (3.10) and (3.9). For a well penetrating in the x-direction, for example, the quantities k_y, k_v, D_y, D_z will be used as $kh = D_x(K_y k_v)^{1/2}$.

3.2 Fundamental of Skin Factor

The idea of skin factor was introduced to petroleum industry by Hurst [11] and van Everdingen [12]. They noticed that for a given flow rate, the measured bottom-hole flowing pressure was less than that calculated theoretically. This indicated to them that there was an additional pressure drop over the theoretical calculation. This is shown in Figure 3.6.

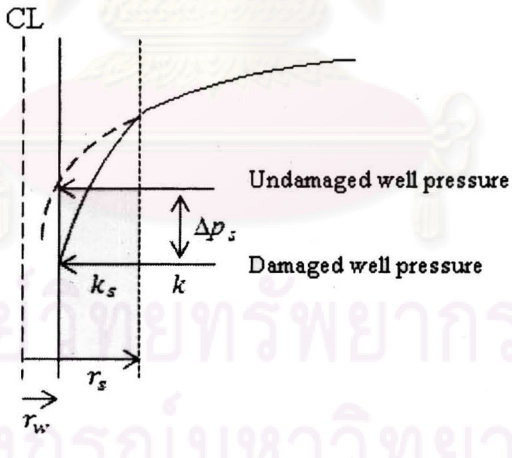

Figure 3.6: Pressure profiles for a well with and without skin. [13]

The pressure drop across the skin zone Δp_s is the difference between the actual pressure in the well when it is flowing, and the pressure that would have been seen if the well were undamaged. The skin factor is a variable used to quantify the magnitude of the skin effect. The skin factor is actually a dimensionless pressure.

For vertical well, the equation for pseudosteady-state flow can be written in terms of ideal pressure drop, $p_R - p_{wf'}$,

$$p_R - p_{wf'} = \frac{141.2 q_o \mu_o B_o}{kh}[\ln(r_e/r_w) - 0.75] \quad (3.11)$$

where

p_R is the reservoir pressure

$p_{wf'}$ is the wellbore flowing pressure for the case of an ideal well producing under the assumptions of the ideal radial model.

The skin factor, *s*, is defined (in oil field unit as):

$$s = \frac{kh}{141.2 q_{sc} B\mu}\Delta p_s \quad (3.12)$$

or

$$\Delta p_s = \frac{kh}{141.2 q_{sc} B\mu} s \quad (3.13)$$

Since the ideal pressure drop for pseudosteady-state flow is

$$p_R - p_{wf'} = \frac{141.2 q_o \mu_o B_o}{kh}[\ln(r_e/r_w) - 0.75] \quad (3.14)$$

and $p_{wf'} - p_{wf} = \Delta p_s$, then we can combine these equations to express the actual pressure loss $p_R - p_{wf}$ in terms of skin factor, which gives

$$p_R - p_{wf} = \frac{141.2 q_o \mu_o B_o}{kh}[\ln(r_e/r_w) - 0.75 + s] \quad (3.15)$$

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Rearranging equation and solving for rate gives

$$q_o = \frac{kh(p_R - p_{wf})}{141.2\mu_o B_o[\ln(r_e/r_w) - 0.75 + s]} \tag{3.16}$$

Skin, s, is the composite of all nonideal conditions affecting flow, the most important of which are

s_d = formation damage skin

s_{pp} = completion skin due to partial penetration

s_p = perforation skin

s_b = blockage skin

s_G = gravel-pack skin

s_A = outer boundary geometry skin

s_θ = deviated skin

The effect of high-velocity flow is also expressed as an equivalent skin, Dq.

$$D = D_{res} + D_d + D_{dp} + D_G \tag{3.17}$$

where

D_{res} = reservoir high-velocity flow term in the region beyond near-wellbore damage $r > r_a$

D_d = damaged zone high-velocity flow term at $r_w < r < r_a$

D_{dp} = high-velocity flow term in the damaged zone immediately surrounding the perforations

D_G = high-velocity flow term in a gravel-packed perforation

Generally, we are interested only in the pseudosteady-state skin and can neglect the transience of the skin effect. The composite skin factor $s + Dq$ is usually calculated from analysis drawdown and buildup test data. Figure 3.7 is shown model for vertical well with simplified composite skin. The flow converges near the wellbore due to limited entry creating additional pressure drop called partial penetration skin. After that fluid flows into the wellbore through the perforated holes and creates another additional pressure drop so called perforation skin. Then the composite skin results from total of partial penetration skin and perforation skin.

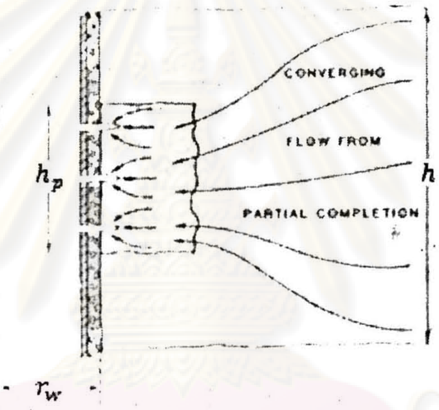

Figure 3.7: Model for simplified composite skin factor. [14]

3.3 Partial Penetration Skin

In some cases, wells are drilled or completed through only a fraction of the total formation to avoid contact with the water zone that may underline the oil or gas zone or perhaps because of difficulties in controlling mud circulation in the pay zone. A completion arrangement where only limited pay-zone interval is open to production is referred to as partial penetration or limited entry.

If a well has limited entry or only partially penetrates through the formation, the flow cannot enter the well over the entire producing interval. Consequently the well will experience a larger pressure drop for a given flow rate than a well that fully penetrates the formation. This geometric effect gives rise to the partial penetration skin effect. It is often useful to estimate the size of the partial penetration skin factor, since it can be subtracted from the apparent skin to determine whether the well is actually damaged.

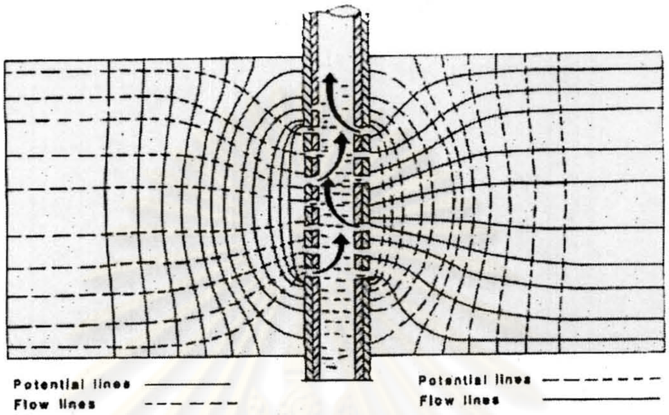

Figure 3.8: Flow behavior of a well with limited entry. (14)

The general characteristics of a well with limited entry are shown in Figure 3.8. Flow lines converge from above and below the open interval, gradually changing to radial flow away from the wellbore. Because of the deformed flow path and localized pressure gradients near the ends of the open interval, lower wellbore flowing pressure is required to produce a given rate.

An important feature of partial penetration is that s_{pp} is always positive, that is, limited entry always reduces the productivity of a well.

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3.3.1 Partial Penetration Skin for Vertical Well

Brons and Marting [1] suggested that the effect of partial penetration and limited entry can be expressed as a skin factor. They gave the simple relation

$$s_{pp} = (1/b - 1)[\ln(h_D) - G(b)] \tag{3.18}$$

where

b	=	fractional penetration
	=	h_p/h
h_D	=	dimensionless pay thickness, $(k/k_v)^{0.5}(h/r_w)$
h_p	=	limited interval open to flow (ft)
h	=	total formation thickness (ft)

$G(b)$ is a function of the fractional penetration

The analytical expression for $G(b)$ can be found directly by algebraic manipulation of Muskat's original solution [15].

$$G(b) = 2.948 + 7.363b + 11.45b^2 - 4.675b^3 \tag{3.19}$$

The value of h_D depends on the placement of the well. The three types of limited-entry configurations are shown in Figure 3.9:

1. A well penetrating the top of the formation
2. A well open to flow from the mid-section of the formation
3. A well with open intervals equally spaced along the entire height of the formation

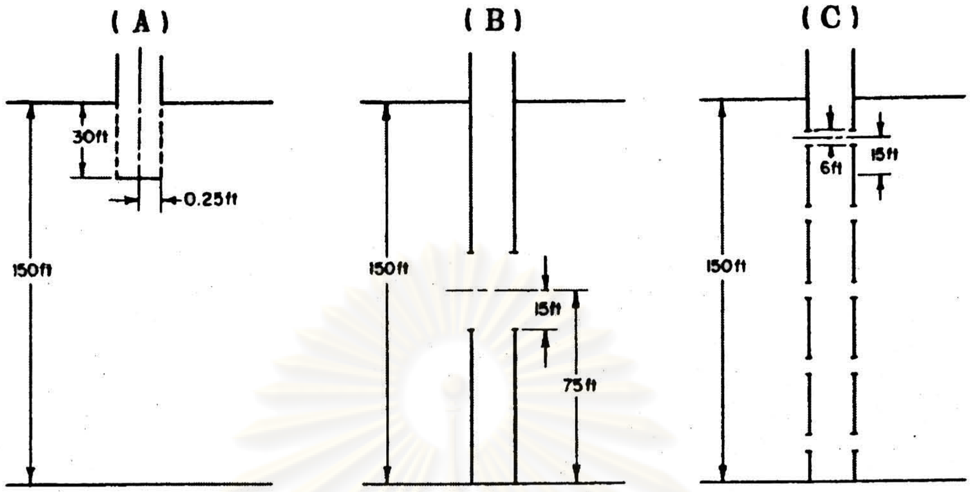

Figure 3.9: Partial penetration and three geometries of limited entry, (A) Well only partially penetrating formation, (B) Well producing from only the central portion of productive interval, and (C) Well with several intervals open to production.[15]

From the example in Figure 3.9, for each case the value of b remains unchanged, but h_D is different for each configuration. For limited entry starting at the top of the formation, total formation thickness h is used to define h_D. If the well is open at the midsection of the formation, $h/2$ is used to define h_D as $h_D = (k/k_v)^{0.5}(h/2r_w)$. For *N* sections of open interval located symmetrically about the middle of the formation, with equal thickness and equally spaced, the correct expression for h_D is $(k/k_v)^{0.5}(h/2Nr_w)$.

3.3.2 Partial Penetration Skin for Horizontal well

For horizontal wells, there is only Babu & Odeh equation that can determine partial penetration skin directly. In order to find partial penetration s_{pp} we have to determine the extra pressure drop caused by partial penetration.

3.3.2.1 Determination of Partial Penetration Skin by Babu & Odeh Equation

As mentioned before, the value s_{pp} accounts for the skin factor due to partial penetration of the horizontal well in the areal plane. $s_{pp} = 0$ when $L = 2x_e$. If $L < 2x_e$, then the value of partial penetration skin factor s_{pp} depends upon the following two conditions:

Case 1. $2y_e/\sqrt{k_y} \geq 1.5x_e/\sqrt{k_x} \gg 0.75h/\sqrt{k_v}$

Case 2. $2x_e/\sqrt{k_x} > 2.66y_e/\sqrt{k_y} \gg 1.33h/\sqrt{k_v}$

It is assumed that $2x_e$ and $2y_e$ will be orders of magnitude larger than h so that $h/\sqrt{k_z}$ is always less that $2y_e/\sqrt{k_y}$ and $2x_e/\sqrt{k_x}$. If this does not hold, the exact solution shows that there will be no productivity advantage in drilling a horizontal well in place of a vertical well.

Case 1: $2y_e/\sqrt{k_y} \geq 1.5x_e/\sqrt{k_x} \gg 0.75h/\sqrt{k_v}$

As stated previously, $s_{pp} = 0$ when $L = 2x_e$

$$s_{pp} = P_{xyz} + P'_{xy} \tag{3.20}$$

Here, the P_{xyz} component is a result of the degree of penetration (the value of $L/2x_e$), and the P'_{xy} component is a result of the location of the well in the x-y plane. The skin component resulting from the z location is negligible and is ignored.

$$P_{xyz} = \left(\frac{2x_e}{L} - 1\right)\left[\ln\frac{h}{r_w} + 0.25\ln\frac{k_y}{k_v} - \ln\left(\sin\frac{180°z_w}{h}\right) - 1.84\right] \tag{3.21}$$

$$P'_{xy} = \frac{2(2x_e)^2}{Lh}\sqrt{k_v/k_x}\{f(x) + 0.5[f(y_1) - f(y_2)]\} \tag{3.22}$$

where f represents a function. The terms in parenthesis after f are their arguments defined as

$$x = \frac{L}{4x_e}, \quad y_1 = \frac{4x_w + L}{4x_e}, \text{and } y_2 = \frac{4x_w - L}{4x_e} \tag{3.23}$$

Additionally, pressure computations are made at the mid-point along the well length, and function $f(x)$ is defined as

$$f(x) = -x[0.145 + \ln(x) - 0.137(x)^2] \tag{3.24}$$

The evaluation of $f(y_1)$ and $f(y_2)$ depends on their arguments, $[(4x_w + L)/(4x_e)]$ and $[(4x_w - L)/(4x_e)]$, respectively. If the arguments, $(y_1 \text{ or } y2\,) \leq 1$, the upper equation is used by replacing x with y_1 or y_2. On the other hand, if $(y_1 \text{ or } y2\,) > 1$, then the following equation is used:

$$f(y) = (2 - y)[0.145 + \ln(2 - y) - 0.137(2 - y)^2] \tag{3.25}$$

where $\quad y = y_1 \text{ or } y_2$

Case 2: $2x_e/\sqrt{k_x} > 2.66y_e/\sqrt{k_y} \gg 1.33h/\sqrt{k_v}$

$$s_{pp} = P_{xyz} + P_y + P_{xy} \tag{3.26}$$

$$P_{xyz} = \left(\frac{2x_e}{L} - 1\right)\left[\ln\frac{h}{r_w} + 0.25\ln\frac{k_y}{k_v} - \ln\left(\sin\frac{180°z_w}{h}\right) - 1.84\right] \tag{3.27}$$

$$P_y = \frac{6.28(2x_e)^2}{2y_e h}\frac{\sqrt{k_y k_v}}{k_x}\left[\left\{\frac{1}{3} - \frac{x_w}{2x_e} + \left(\frac{x_w}{2x_e}\right)^2\right\} + \frac{L}{48x_e}\left(\frac{L}{2x_e} - 3\right)\right], \tag{3.28}$$

$$P_{xy} = \left(\frac{2x_e}{L} - 1\right)\frac{6.28(2y_e)}{h}\sqrt{\frac{k_v}{k_y}}\left[\frac{1}{3} - \frac{y_w}{2y_e} + \left(\frac{y_w}{2y_e}\right)^2\right] \tag{3.29}$$

for $[\min\{y_w, (2y_e - y_w)\} \geq 0.5\, y_e]$

3.3.2.2 Determination of Partial Penetration Skin by Pressure Drop

Since there is only Babu & Odeh analytical equation can determine partial penetration skin factor, s_{pp}, directly, so partial penetration skin factor from other methods (Joshi *et al.*, Goode & Kuchuk analytical equations, PROSPER software and reservoir simulator) can be determined by the extra pressure drop calculation.

The extra pressure drop caused by the effect of the partial penetration well can be determined by:

$$\Delta p_{pp} = \Delta p_{w,fp} - \Delta p_{w,pp} \tag{3.30}$$

where Δp_{pp} is the extra pressure drop, $\Delta p_{w,fp}$ is pressure drop from fully penetrating horizontal well and $\Delta p_{w,pp}$ is pressure drop from partial penetrating horizontal well.

The pressure drops, $\Delta p_{w,fp}$ and $\Delta p_{w,pp}$, can be determined by the inflow performance equation where $\Delta p = p_R - p_{wf}$.

Then s_{pp} is caculated from following equation;

for vertical and slightly deviated well:

$$s_{pp} = \frac{\Delta p_{pp}(h)\sqrt{k_x k_y}}{141.2 q_o B_o \mu_o} \tag{3.31}$$

for horizontal and highly deviated well:

$$s_{pp} = \frac{\Delta p_{pp}(2x_e)\sqrt{k_v k_h}}{141.2 q_o B_o \mu_o} \tag{3.32}$$

Note that this partial penetration skin factor calculation is based on Babu & Odeh equation then the values obtained are use for comparison only and cannot applied in other analytical equations.

3.4 Deviated Skin

Roemershuser and Hawkins[5], studied steady state flow in a reservoir producing through a fully penetrating slanted well by using an electrical model. They considered a circular reservoir of finite extent and concluded that the slant of fully penetrating well causes an increase in the well productivity compared with a vertical well. The increase in well productivity results from the decrease in the resistance to flow around the wellbore due to the increase in the producing interval area exposed to flow. This increase in well productivity indicates that a fully penetrating slanted well creates a negative skin effect.

Cinco *et al.* [6], Besson [7] and Rogers and Economides [8] have developed correlations to determine the skin factor, s_θ. Cinco *et al.* [6] defined this version of the skin factor as functions of deviation angle and dimensionless thickness:

$$s_\theta = -\left(\frac{\theta'_w}{41}\right)^{2.06} - \left(\frac{\theta'_w}{56}\right)^{1.865} \times \log\left(\frac{h_D}{100}\right) \tag{3.33}$$

For $0° \le \theta'_w \le 75°$, and $\theta'_w = \tan^{-1}\left(\sqrt{\frac{k_v}{k_h}}\tan\theta_w\right)$ and $h_D = \frac{h}{r_w}\sqrt{\frac{k_h}{k_v}}$

Later, Besson [7] studied performances of slanted and horizontal wells using the definition of a geometrical skin. Besson [7] obtained the following correlation of skin for slanted wells:

$$s_\theta = \ln\left(\frac{4r_w}{L\alpha\gamma}\right) + \frac{h}{\gamma L}\ln\left(\frac{\sqrt{Lh}}{4r_w}\frac{2\alpha\sqrt{\gamma}}{1+1/\gamma}\right) \tag{3.34}$$

where $\alpha = \sqrt{k_h/k_v}$, and $\gamma = \sqrt{\cos^2\theta + \frac{1}{\alpha^2}\sin^2\theta}$

More recently, Rogers and Economides [8] presented a correlation for skin factor to account for slant of deviated wells:

$$s_\theta = -1.64\frac{(\sin\theta)^{1.77}(h_D)^{0.184}}{\left(\sqrt{k_h/k_v}\right)^{0.821}} \qquad \text{for } \sqrt{\frac{k_h}{k_v}} < 1 \tag{3.35}$$

and

$$s_\theta = -2.84\frac{(\sin\theta)^{5.87}(h_D)^{0.152}}{\left(\sqrt{k_h/k_v}\right)^{0.964}} \qquad \text{for } \sqrt{\frac{k_h}{k_v}} \geq 1 \qquad (3.36)$$

where $h_D = h/r_w$.

Since the zero degree of deviation is vertical well and the 90 degree of deviation is horizontal well, we categorize the different degrees of deviation into two kinds of deviated well based on these correlation.

A well with $0° < \theta \leq 75°$ is defined as a slightly deviated well. The inflow and skin factor for this type of deviated well is then compared to those for vertical wells.

A well with $75° < \theta \leq 90°$, is defined as a highly deviated well. The inflow and skin factor for this type of deviated well is compared to those for the horizontal wells.

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CHAPTER IV

RESULTS AND DISCUSSION

The effect of the pressure drop around the horizontal wellbore caused by partial penetration in the reservoir is studied using analytical equations, PROSPER software, and reservoir simulation. The hypothetical reservoirs and well models were constructed using ECLIPSE 100. Numerous simulations investigating different parameters were run in order to determine the partial penetration skin. Different reservoir and well properties were used in the models in order to study the effect of each parameter. The reservoir dimensions, fluid properties, and reservoir properties are similar to Retnanto and Yamin [(16)] study.

4.1 Horizontal Well Partial Penetration Skin

4.1.1 Determination of Partial Penetration Skin Using Analytical Equations and PROSPER Software

This section illustrates the computation of partial penetration skin factor using analytical equations proposed by (1) Joshi *et al.*, (2) Babu & Odeh, (3) Goode & Kuchuk, and (4) PROSPERS software. A simple reservoir geometry as shown in Figure 4.1 is used in the skin calculation. In order to study the effect of different parameters on skin factor, we vary reservoir thickness, permeability ratio, well length, wellbore diameter, and oil gravity and compare the results. Table 4.1 shows the reservoir variables used in this study.

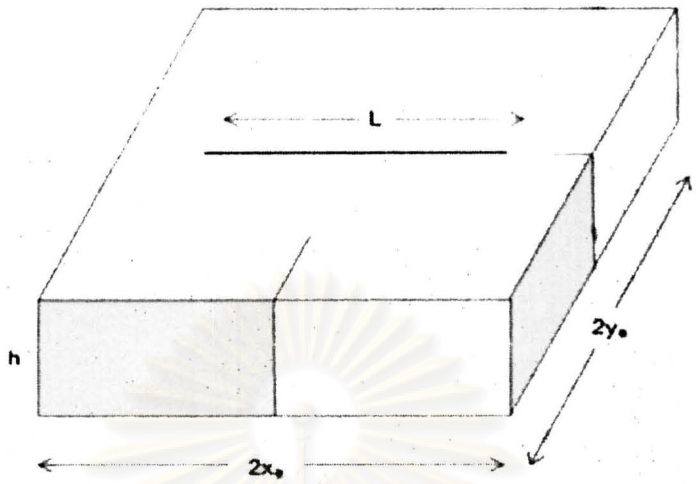

Figure 4.1: Horizontal well and reservoir configuration.

Table 4.1: General reservoir condition for case studies

Reservoir dimension, $2x_e$	5000 ft
Reservoir dimension, $2y_e$	5000 ft
Reservoir thickness, h	50, 100, and 250 ft
Permeability, k_z/k_h	0.01, 0.1 and 1
Horizontal well length:	
Fully open well	5000 ft
20% partial penetration well	1000 ft
40% partial penetration well	2000 ft
60% partial penetration well	3000 ft
80% partial penetration well	4000 ft
Horizontal well diameter	3.625, 5.875 and 8.5 inch
Oil gravity, °API	15, 30, 45, and 60°API

The partial penetration skin factor determined by Joshi *et al.* and Goode & Kuchuk analytical equations can be obtained by pressure different between two cases, fully and partially penetrating well model. First, we calculate $(p_R - p_{wf})$ from both fully and partially penetrating well models, and then subtract the pressure drop of partially penetrating well models by the pressure drop of fully penetrating well models to obtain the extra pressure drop caused by the partial penetration. Finally, the partial penetration skin factor can be determined by equation (3.32). Figure 4.2 shows the flowchart for determined partial penetration skin factor from analytical equations.

Note that partial penetration skin factor from Babu & Odeh analytical equation can be determined by (1) calculate by Babu & Odeh equation in section 3.2.2.1 or (2) calculate the extra pressure drop same as Joshi *et al.* and Goode & Kuchuk analytical equations.

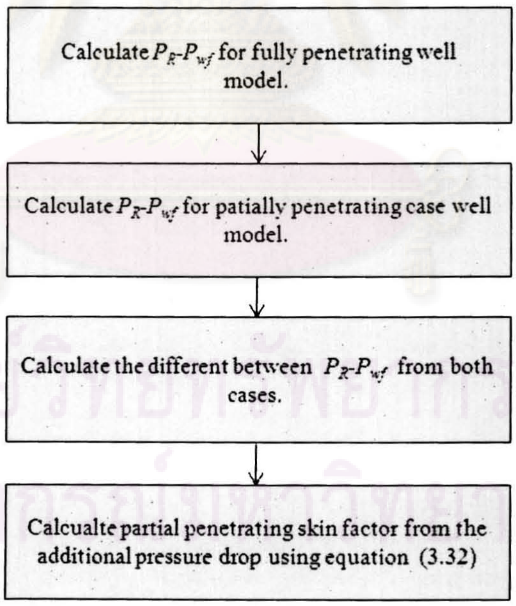

Figure 4.2: Determination of partial penetration skin factor from analytical equations.

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The partial penetration skin factor determined by PROSPER software are also obtained by pressure different between two cases, fully and partially penetrating well model. First, we calculate pressure drop $(p_R - p_{wf})$ from the well performance for both fully and partially penetrating well models in order to see the extra pressure drop caused by partial penetration. Then the partial penetration skin factor is determined by adding the number of skin as pseudo-damage skin into the fully penetrating well model. We adjust this value of skin factor until pressure drop is matched with that from the partially penetrating well model. Figure 4.3 shows the flowchart for determined partial penetration skin factor from PROSPER software.

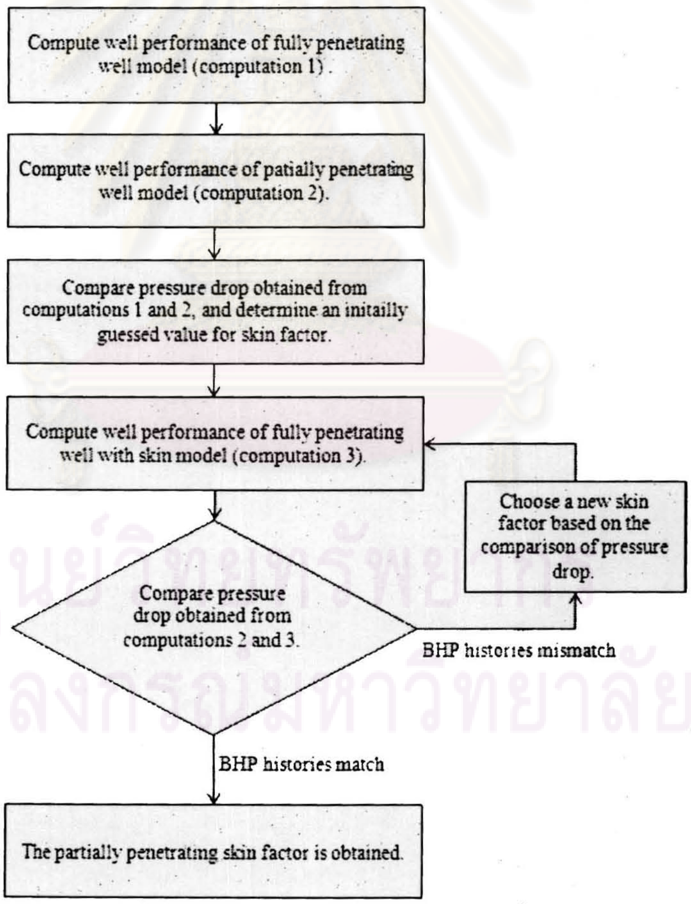

Figure 4.3: Determination of partial penetration skin factor from PROSPER software.

This section aims to compare the effect of the pressure drop caused by the well which partially penetrates into the reservoir. The base case is set and compared with various cases. Table 4.2 shows the details of each case. All cases study the effect of different parameters. Cases 1 and 2 focus on the reservoir thickness. Cases 3 and 4 study the effect of anisotropic ratio (k_v/k_h) by changing it 1 to 0.01 and 0.1, respectively. Cases 5 and 6 study the effect of the wellbore diameter. Case 7 to 9 study the effect of fluid properties, where B_o and μ_o are changed as oil gravity (°API) changed.

Table 4.2: Details of each case.

Case	Base	1	2	3	4
Reservoir thickness, *h* (ft)	100	50	250	100	100
Permeability, k_z/k_h	1	1	1	0.01	0.1
Horizontal well diameter (in.)	5.875	5.875	5.875	5.875	5.875
Oil gravity, °API	30	30	30	30	30

Case	5	6	7	8	9
Reservoir thickness, *h*	100	100	100	100	100
Permeability, k_z/k_h	1	1	1	1	1
Horizontal well diameter	3.625	8.5	5.875	5.875	5.875
Oil gravity, °API	30	30	15	45	60

The results of all cases are shown in Figures 4.4 to 4.13 as a comparison between the calculated results of three analytical equations: Joshi *et al.*, Babu & Odeh and Goode & Kuchuk and results determined by PROSPER based on Babu & Odeh equation and Goode & Kuchuk equation. The results are plotted as partial penetration skin factor (PP skin factor) versus percentage of the horizontal well partially penetrated into the reservoir (%penetration).

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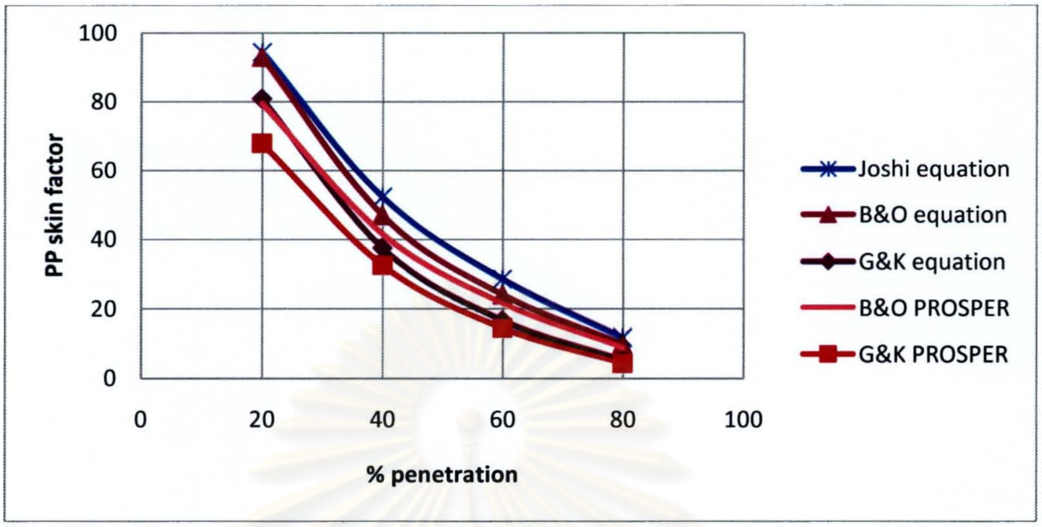

Figure 4.4: Partial penetration skin factor for base case.

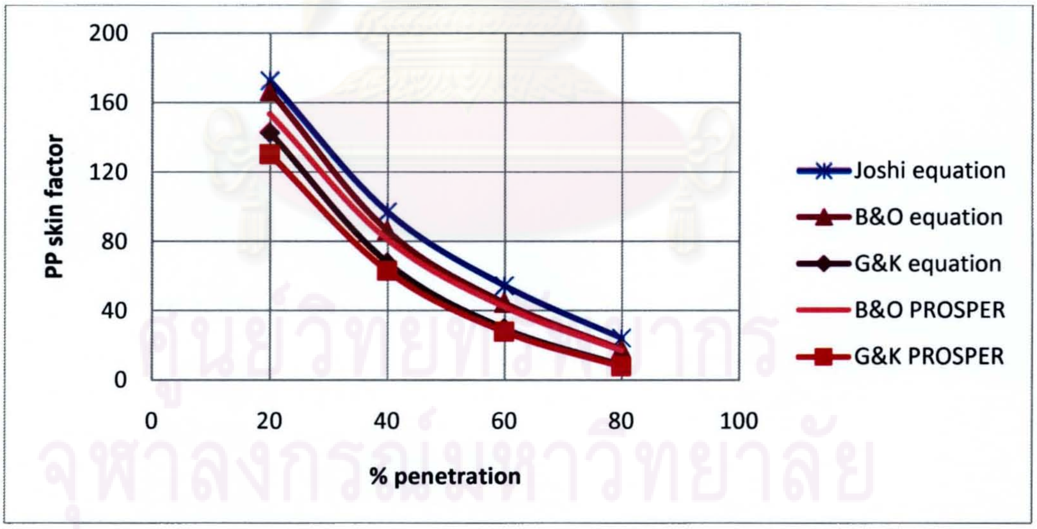

Figure 4.5: Partial penetration skin factor for case 1.

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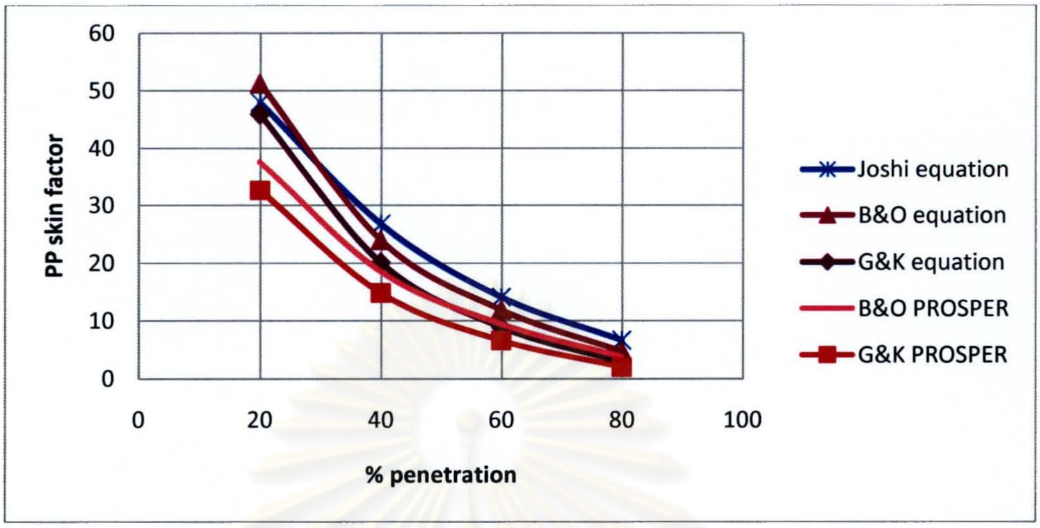

Figure 4.6: Partial penetration skin factor for case 2.

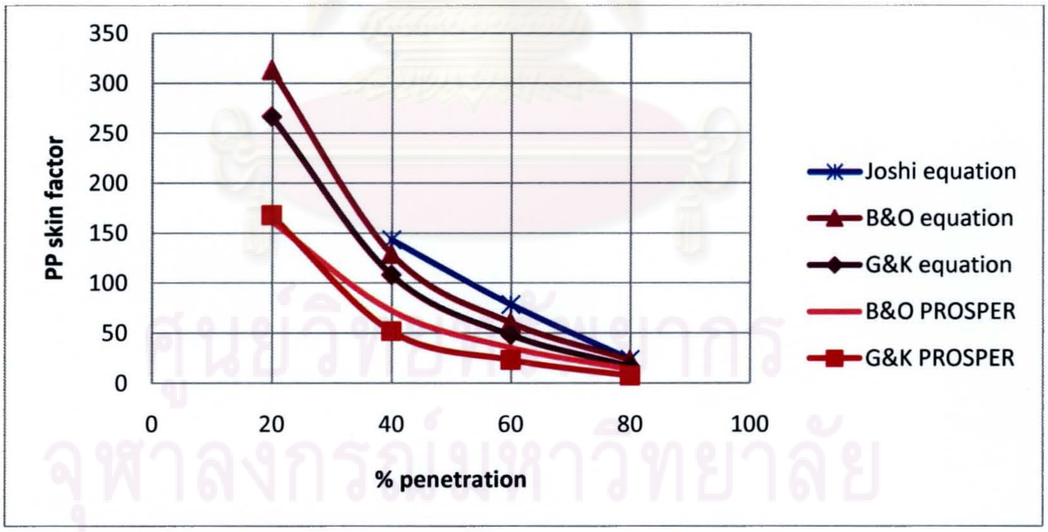

Figure 4.7: Partial penetration skin factor for case 3. *

*Joshi equation cannot determine partial penetration skin factor for 20% penetration. Small value of anisotropic ratio (0.01) and small value of reservoir thickness (50 ft), cause the dimensionless length L_D to be less than 1, which is the minimum range of L_D.

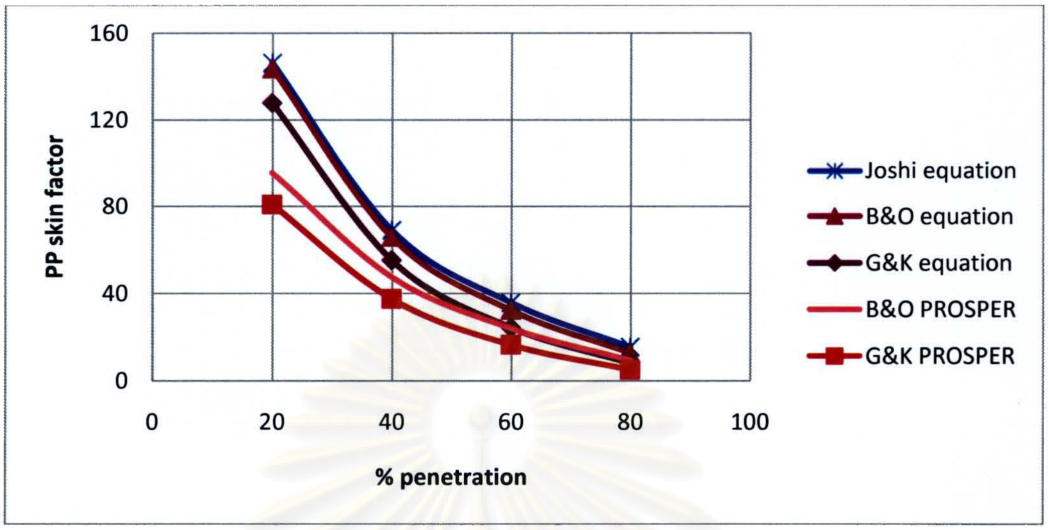

Figure 4.8: Partial penetration skin factor for case 4.

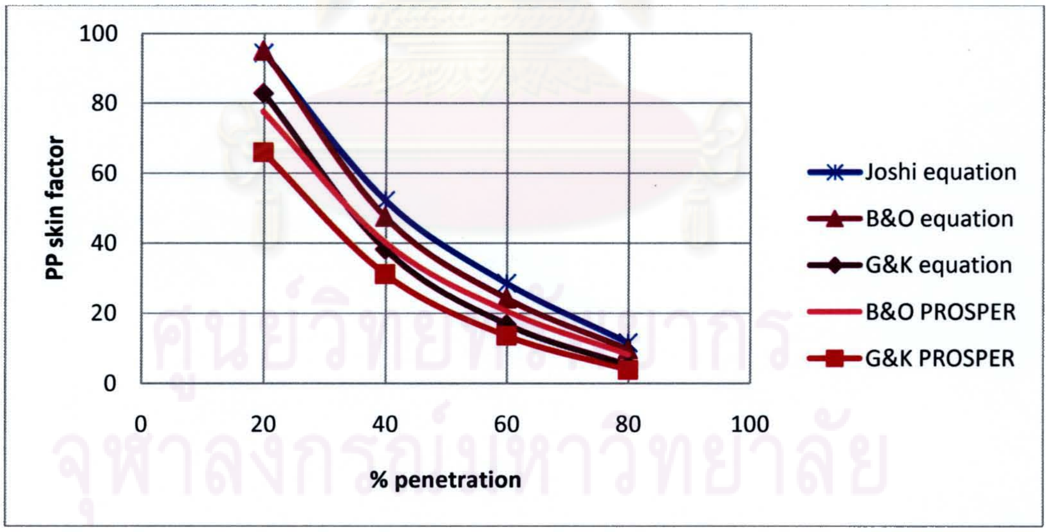

Figure 4.9: Partial penetration skin factor for case 5.

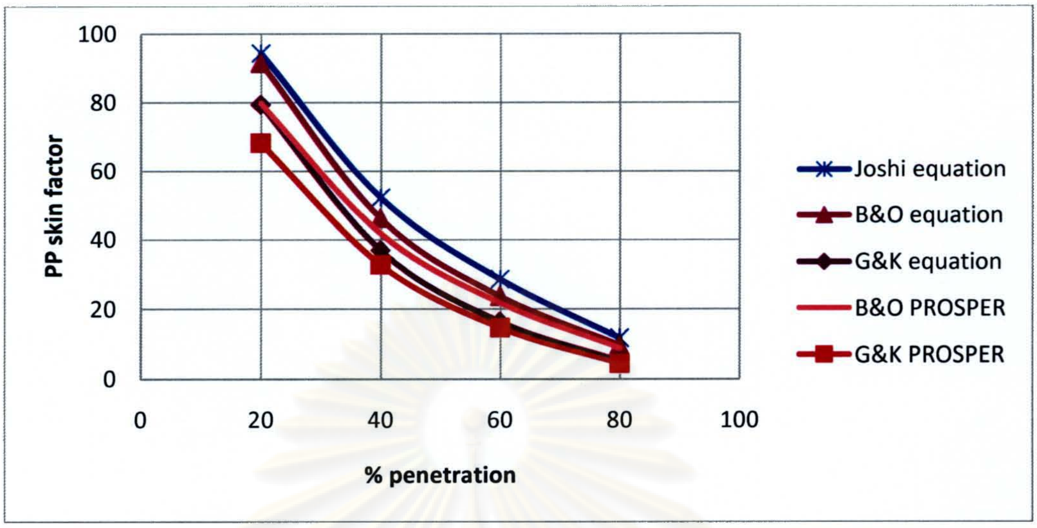

Figure 4.10: Partial penetration skin factor for case 6.

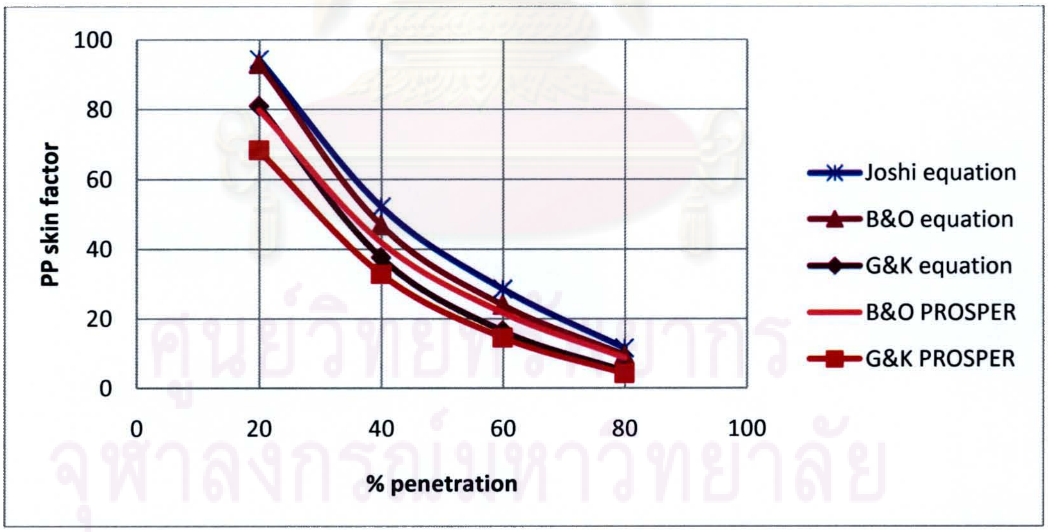

Figure 4.11: Partial penetration skin factor for case 7.

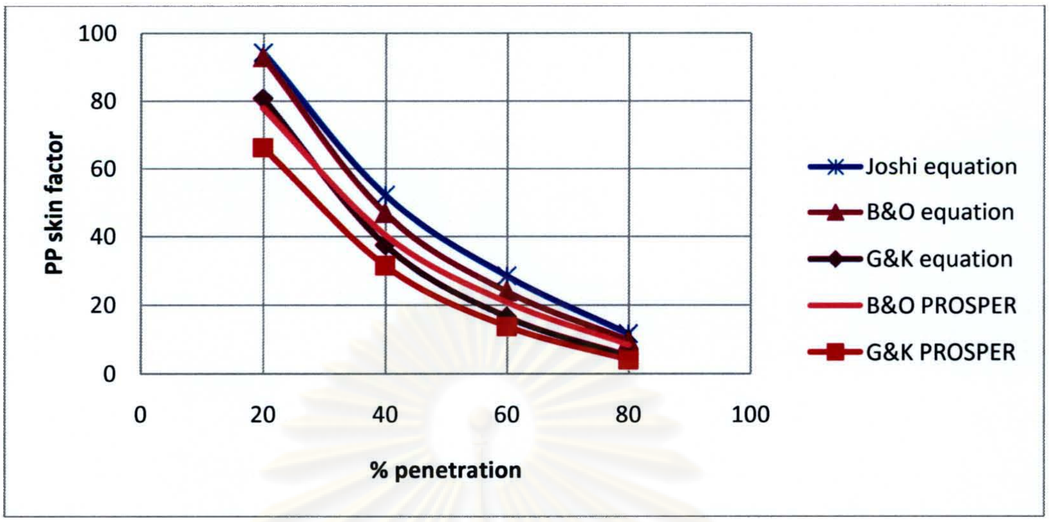

Figure 4.12: Partial penetration skin factor for case 8.

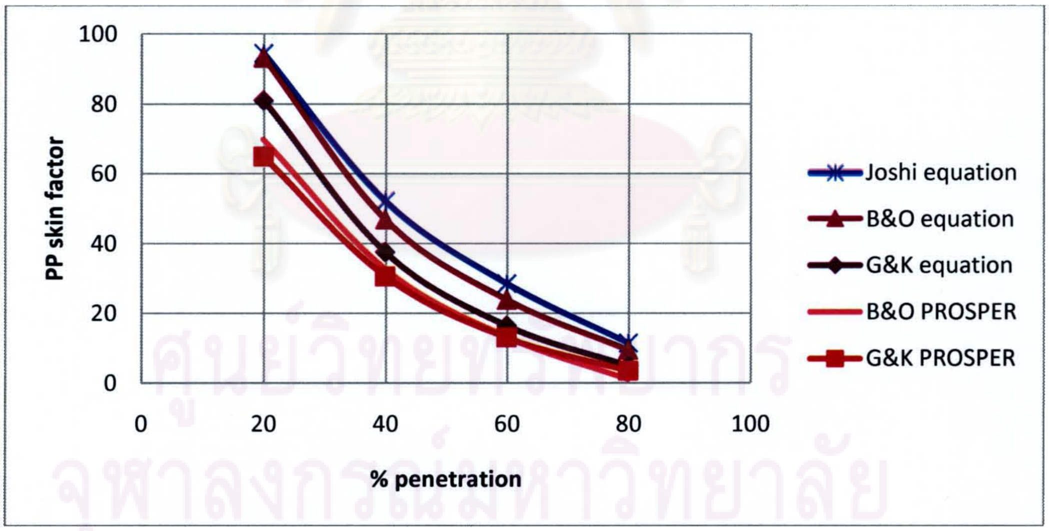

Figure 4.13: Partial penetration skin factor for case 9.

The results from all cases show that the relationship between partial penetration skin factor and the percent penetration are in the same trends. The value of partial penetration skin factor determined by Joshi equation is almost the highest value and the partial penetration skin factor determined by Goode and Kuchuk equation is the lowest. Note that, in some cases, Joshi equation cannot determine the PP skin factor due to the limitation in the low percent penetration.

The partial penetration skin factors increase as the percent penetration decrease because the limit entry of the connection between wellbore and reservoir, and the converged flow create the additional pressure drop.

For ease of parameters selection for further partial penetration skin factor study using reservoir simulation, we average the partial penetration skin factors in order to represent the results from all methods, then plots as a comparison of each parameter. The plots of average partial penetration skin factor are shown in Figure 4.14 to Figure 4.17.

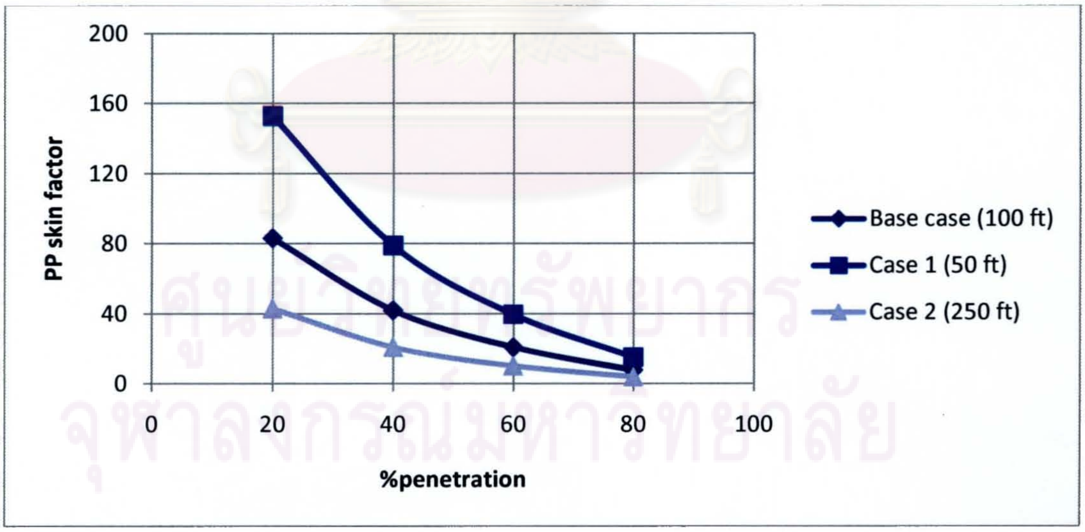

Figure 4.14: The comparison of the average partial penetration skin factor from all methods for different reservoir thickness.

Figure 4.14 shows the comparison of average partial penetration skin factor for reservoir thickness 50, 100 and 250 ft. The results illustrate that the thinner the reservoir, the higher the partial penetration skin factor. Additionally, it is also important to note that thick reservoir have more reserves than thin reservoir.

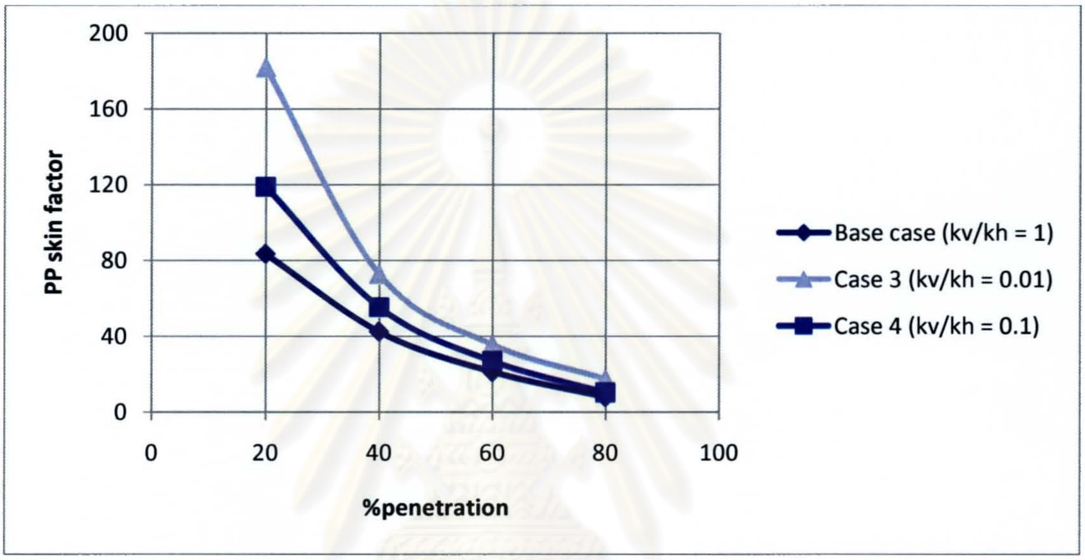

Figure 4.15: The comparison of the average partial penetration skin factor from all methods for different reservoir anisotropic ratios.

Figure 4.15 shows the comparison of average partial penetration skin factor for reservoir anisotropic ratios of 0.01, 0.1 and 1. The results illustrate that the partial penetration skin factor is the reverse variation to the anisotropic ratio. A decrease in vertical permeability results in an increase in vertical-flow resistance and decrease in oil production rate, in order to maintain the production rate the pressure drop must be higher.

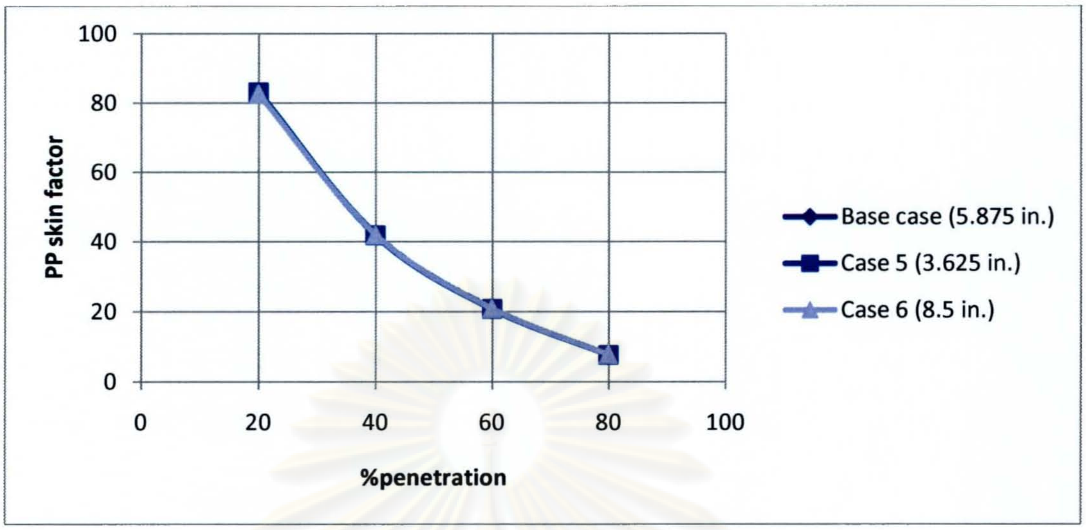

Figure 4.16: The comparison of the average partial penetration skin factor from all methods for different well diameters.

Figure 4.16 shows the comparison of average partial penetration skin factor for well diameter of 3.625, 5.875 and 8.5 inches. The results depict a little difference between the cases.

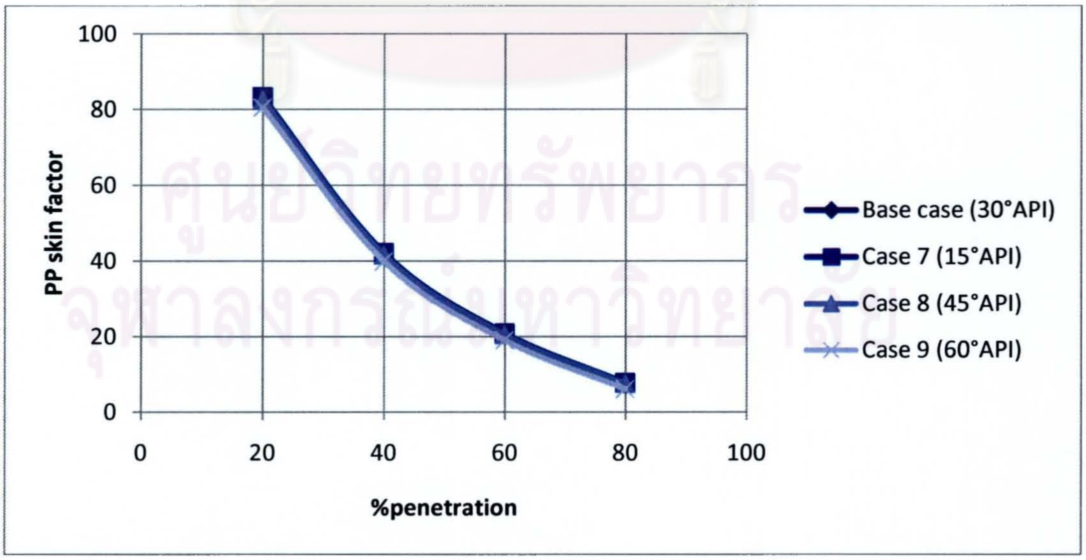

Figure 4.17: The comparison of the average partial penetration skin factor from all methods for different oil gravity.

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Figure 4.17 shows the comparison of average partial penetration skin factor for oil gravity of 15, 30, 45 and 60 degree API. The results show non to little difference between the cases. In summary, partial penetration skin factor is sensitive to the reservoir thickness and permeability anisotropic ratio but is not sensitive to wellbore diameter and oil gravity.

4.1.2 Determination of Partial Penetration Skin Using Reservoir Simulation

In order to study the effect of the pressure drop around a horizontal wellbore on the well performance caused by the well partially penetrated into the reservoir, a hypothetical reservoir model was constructed using ECLIPSE100 (product of Schlumberger). ECLIPSE100 can support several requirements such as:

1. Completion in selected interval with adjustable skin value.
2. Extremely fine grid model can be constructed for more accuracy in determining the fluid flow behavior in the reservoir, especially around the wellbore.

The hypothetical reservoir model is a simple rectangular reservoir with one horizontal well in the middle of the Y-Z plane penetrating in the X direction. Since the partial penetration skin must be determined by the pressure drop caused by flow restriction of the well, the nearby grids around the horizontal well are refined as very fine grid.

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Reservoir model

The reservoir with the drainage area of 5,000 x 5,000 ft is divided into 100 columns in the X direction and 51 rows in the Y direction. The X grids are equally divided into 50 ft each. The Y grid block dimensions are exponentially increased away from both side of the horizontal well. The vertical interval is presented by 51 layers. The 100 ft thickness was equally distributed except the middle grid which is 1 ft thick for every case in order to place the horizontal well. The 3-D view of the actual simulation grid is illustrated in Figure 4.18. The reservoir was assumed to be homogeneous with 15% porosity. Table 4.3 gives the reservoir variables used in the study.

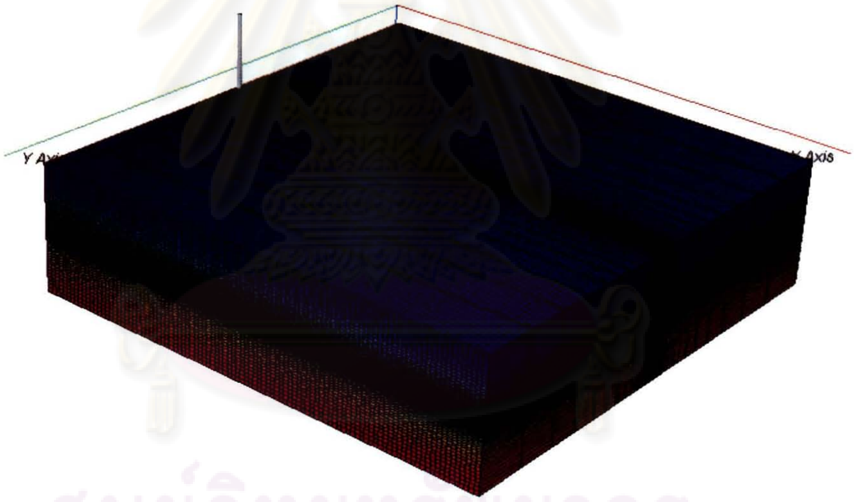

Figure 4.18: 3-D view of the actual simulation grid.

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Table 4.3: General reservoir variables for case studies.46

Reservoir dimension, $2x_e$	5000 ft
Reservoir dimension, $2y_e$	5000 ft
Reservoir thickness, h	50, 100, and 250 ft
Permeability, k_z/k_h	0.01, 0.1 and 1
Porosity, ϕ	15%
Total compressibility, c_t	$3x10^{-5}$ psi^{-1}
Datum depth	4000 ft
Initial pressure @ mid-perforation	2500 psi
Reservoir temperature	200°F

Horizontal Well Model

The type of completion of the horizontal well used in this simulation study is open-hole completion. The horizontal well is placed in the X direction which is equally divided into 100 grids for easily adjusting the partial penetration well model. The well is placed in the middle in each direction. The bottom hole pressure is set at the middle of the reservoir. In this study, the partially penetrated well is determined as a percentage of the reservoir width. For example, Figure 4.19 illustrate fully penetrating well ($L= 2x_e$ = 5,000 ft) and Figure 4.20 illustrate 60 % partially penetrating well (L = 3,000 ft, $2x_e$ = 5,000) Table 4.4 gives the well conditions variables used for these studies.

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Table 4.4: General well conditions for case studies.

Horizontal well length:	
Fully open well	5000 ft
20% partial penetration well	1000 ft
40% partial penetration well	2000 ft
60% partial penetration well	3000 ft
80% partial penetration well	4000 ft
Horizontal well diameter	5.875 inch
Minimum BHP	1000 psi

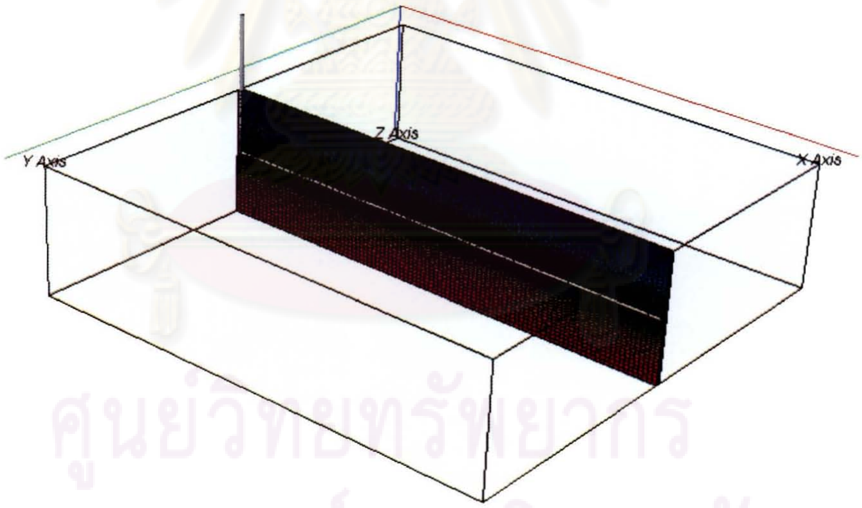

Figure 4.19: Fully open well completion (100% penetration).

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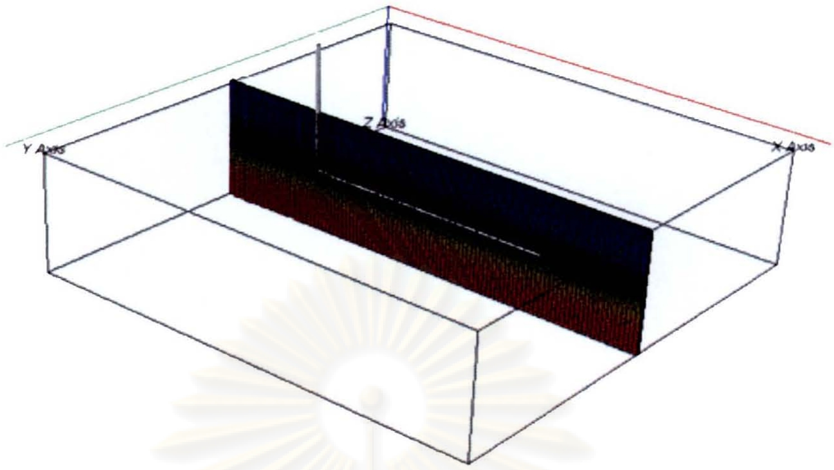

Figure 4.20: Partially penetrated well completion (60% penetration).

Fluid Properties

The initial fluids in the reservoir consist of oil and water. The initial water saturation is equal to 0.2 as connate water. The type of oil used in the study is dead oil with oil gravity of 30°API.

Simulation Study

All reservoir simulation is run with a production rate of 1,000 BPD, and the economic limit of 100 BPD. The bottom hole pressure history for each partially penetrating well model is obtained from the simulation and compared with the pressure history of the fully open well model in order to see the extra pressure drop caused by partial penetration. Then the partial penetration skin is determined by adding the number of skin as pseudo-damage skin into the fully penetrating well model. We adjust this value of skin factor until the pressure history is matched with that from the partially penetrating well model. Figure 4.21 shows the flowchart for determined partial penetration skin factor from reservoir simulation. Figure 4.22 shows the bottom hole pressure histories obtained from 60% partially penetrating well and fully penetrating well without skin. The skin factor is adjusted until the pressure history of the fully penetrating well with skin is matched to the 60% partially penetrating well. After a few trials, the value of skin factor is found to be 14.3.

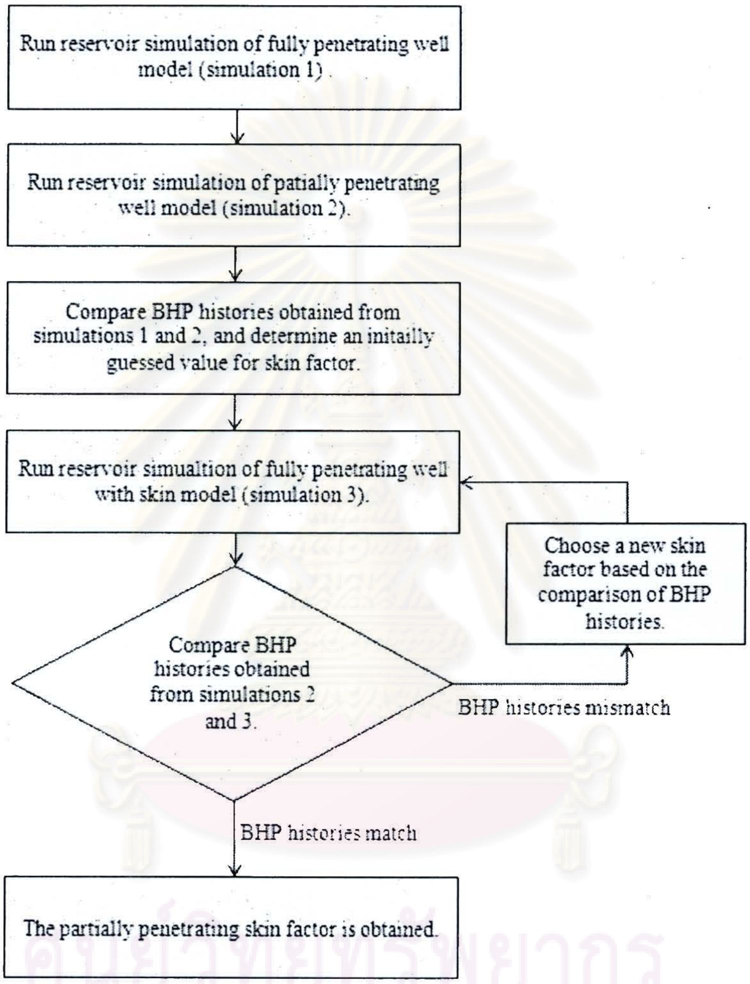

Figure 4.21: Determination of partial penetration skin factor from reservoir simulator, ECLIPSE.

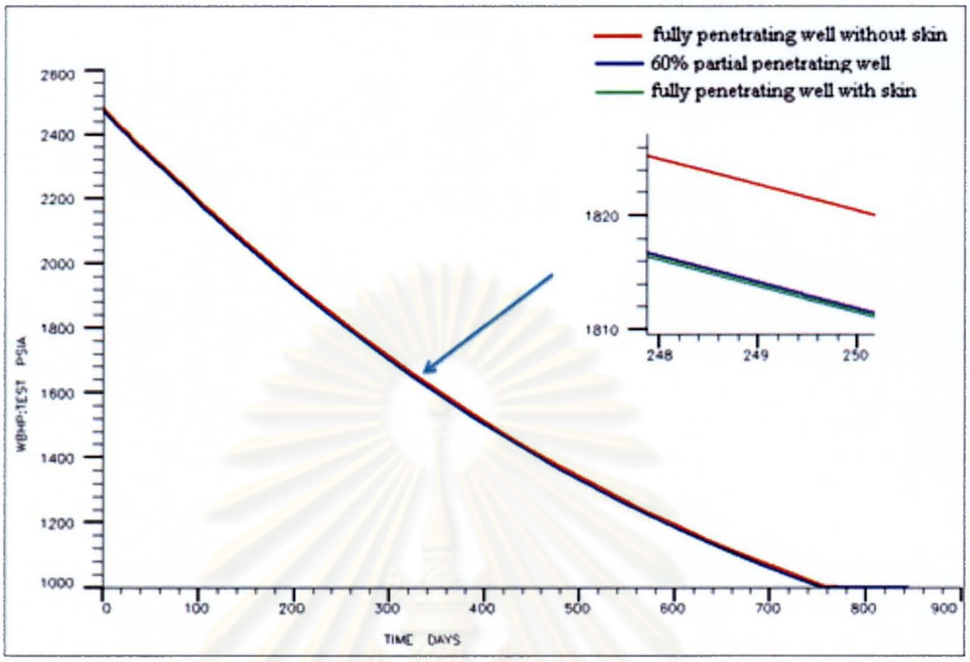

Figure 4.22: Comparison of bottom pressure histories between 60% partially penetrating well, fully penetrating well with skin, and fully penetrating well without skin.

Case Study for Simulation

In Section 4.1, we determined that reservoir thickness and reservoir anisotropic ratio have significant impact on partial penetration skin factor while wellbore diameter and oil gravity do not. Then, the cases to be studied in this section are the base case and cases 1 to 4. The details of each case are reviewed in Table 4.5.

Table 4.5: Details of each case for simulation study.

Case	Base	1	2	3	4
Reservoir thickness, h (ft)	100	50	250	100	100
Permeability, $(k_v/\ k_h)$	1	1	1	0.01	0.1
Horizontal well diameter (in.)	5.875	5.875	5.875	5.875	5.875
Oil gravity, °API	30	30	30	30	30

Figures 4.23 and 4.24 shows additional pressure drop due to partial penetration and partial penetration skin factor for the base case, respectively.

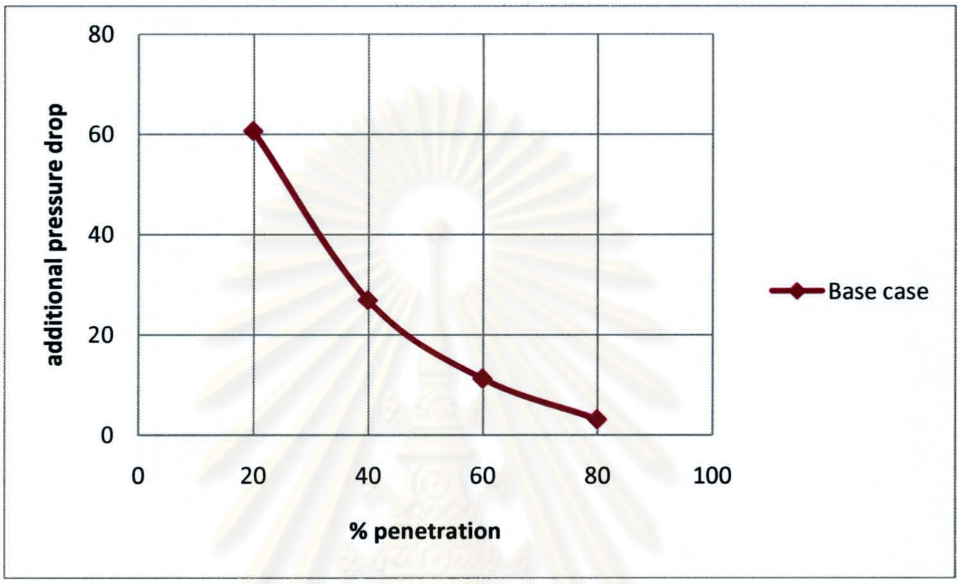

Figure 4.23: Additional pressure drop due to partial penetration for the base case.

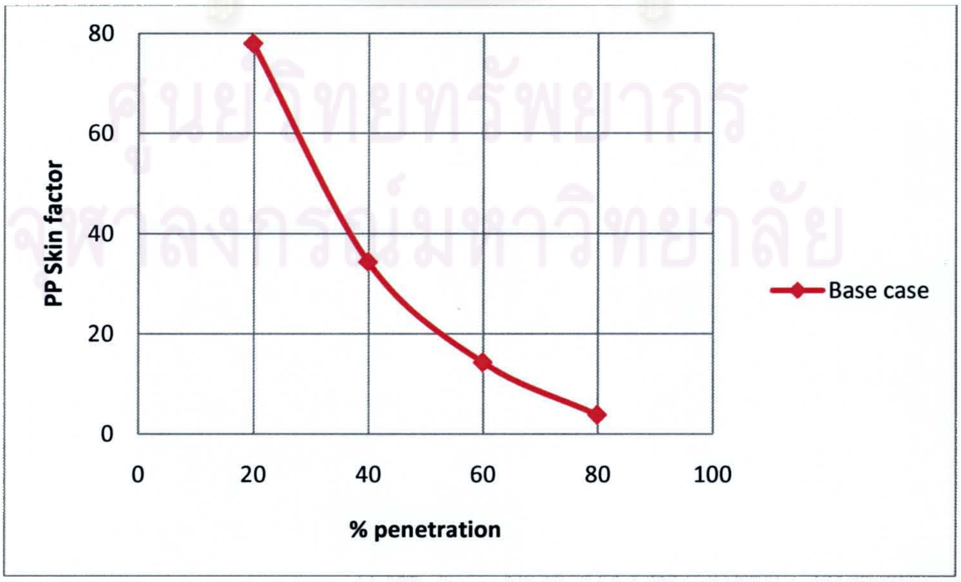

Figure 4.24: Partial penetration skin factor for the base case.

The results from all cases are shown in Figures 4.25 and Figure 4.26. The comparison between different reservoir thicknesses and anisotropic ratios show the same trend as those obtained from the analytical equations and PROSPER software.

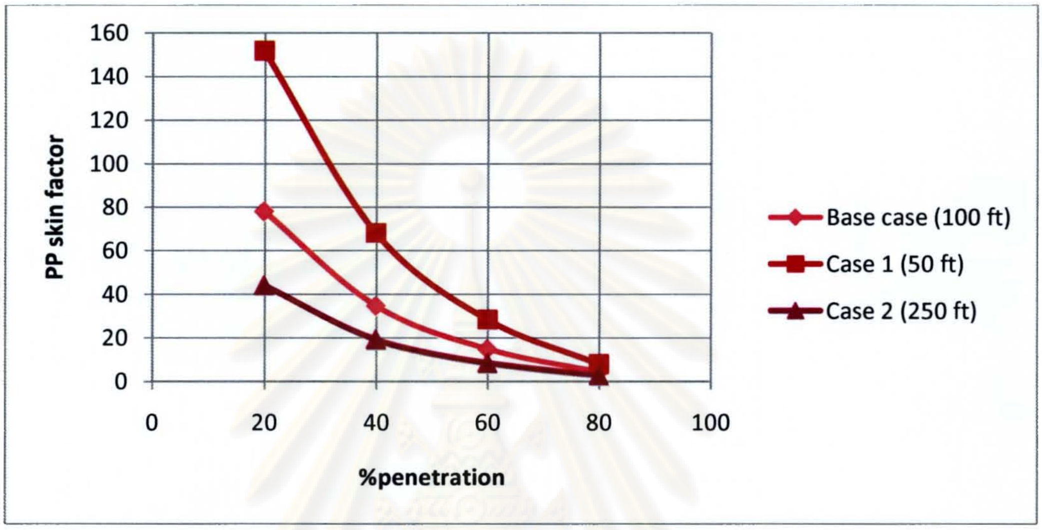

Figure 4.25: Partial penetration skin factor determined from reservoir simulation for different reservoir thicknesses.

Figure 4.25 shows the comparison of average partial penetration skin factor for reservoir thickness 50, 100 and 250 ft. The results illustrate that the thinner the reservoir, the higher the partial penetration skin factor. Additionally, it is also important to note that thick reservoir have more reserves than thin reservoir.

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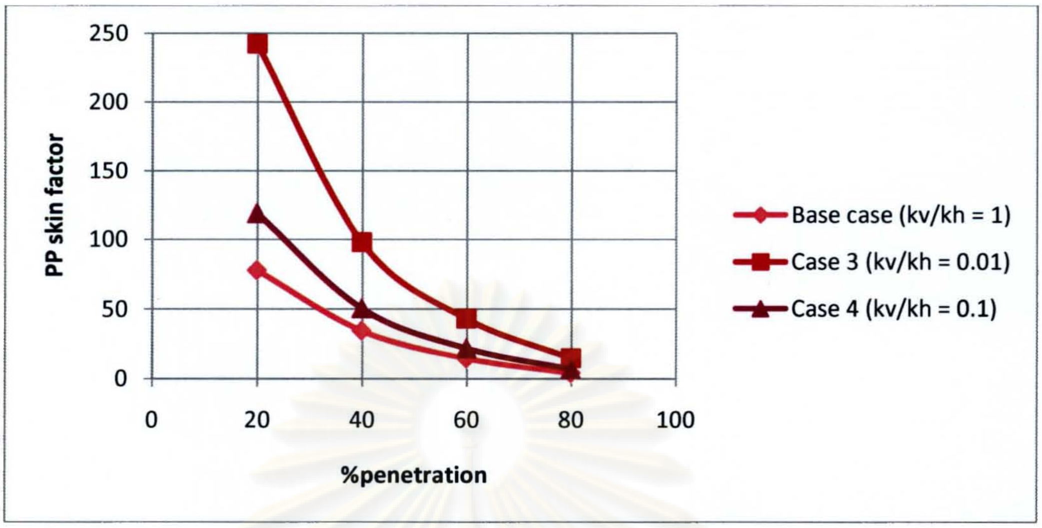

Figure 4.26: Partial penetration skin factor determined from reservoir simulation for different anisotropic ratios.

Figure 4.26 shows the comparison of average partial penetration skin factor for reservoir anisotropic ratios of 0.01, 0.1 and 1. The results illustrate that the partial penetration skin factor is the reverse variation to the anisotropic ratio. A decrease in vertical permeability results in an increase in vertical-flow resistance and decrease in oil production rate, in order to maintain the production rate the pressure drop must be higher.

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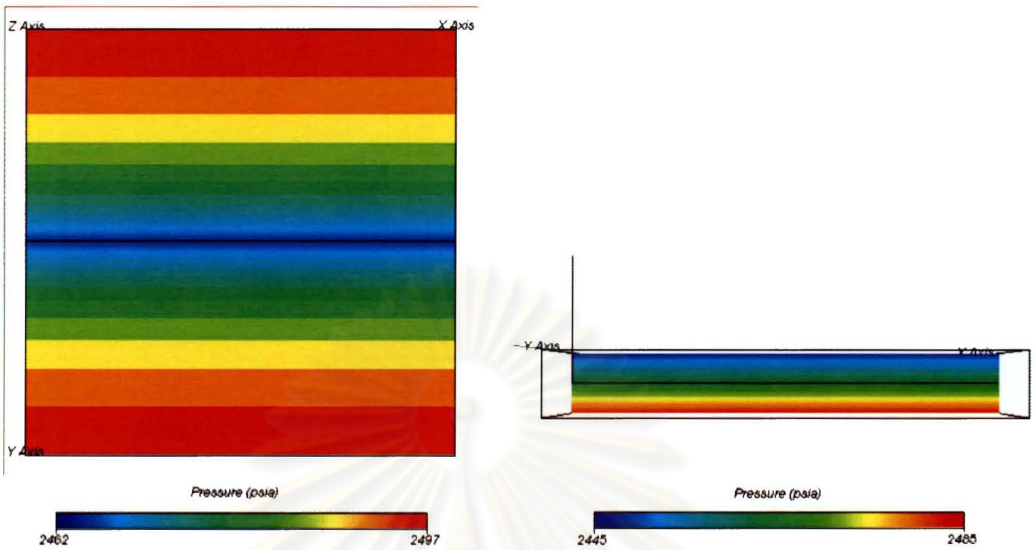

Figure 4.27: Pressure development for Base case with fully penetrating well model (h=100ft, k_v/k_h=1).

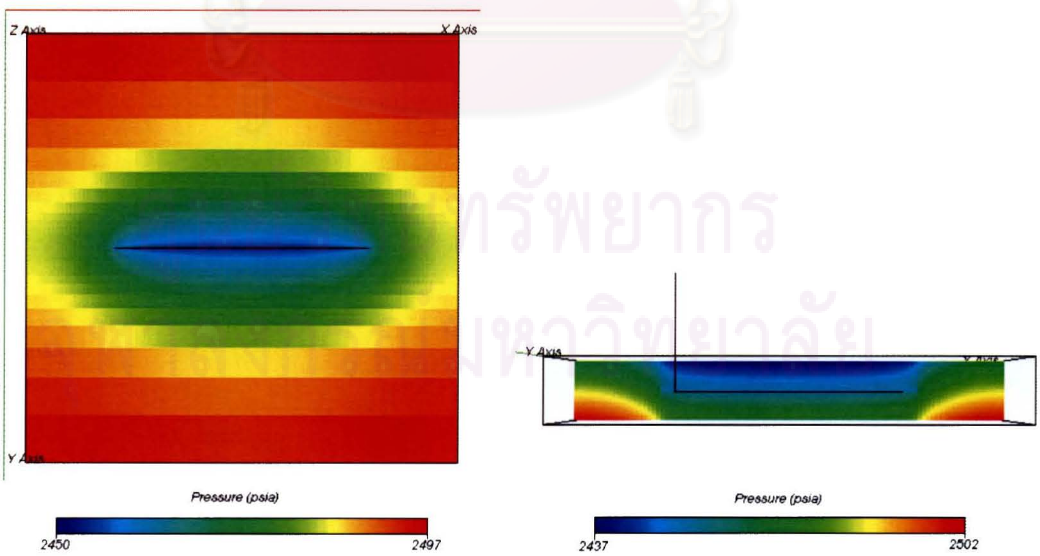

Figure 4.28: Pressure development for Base case with 60% partially penetrating well model (h=100ft, k_v/k_h=1).

Figure 4.27 illustrates a snap shot of pressure development for fully penetrating well model; the pressure develops as linear flow towards the well from both vertical and horizontal flow. Figure 4.28 illustrates pressure development for 60% partially penetrating well model. For horizontal plane, the pressure develops as elliptical flow toward the well. For vertical plane, as the pressure flows from above and below the well try to develop as linear flow towards the well. However, there is high pressure zone existing both edges of the well and create converging flow. The converging flow causes the extra pressure drop as know as partial penetration skin.

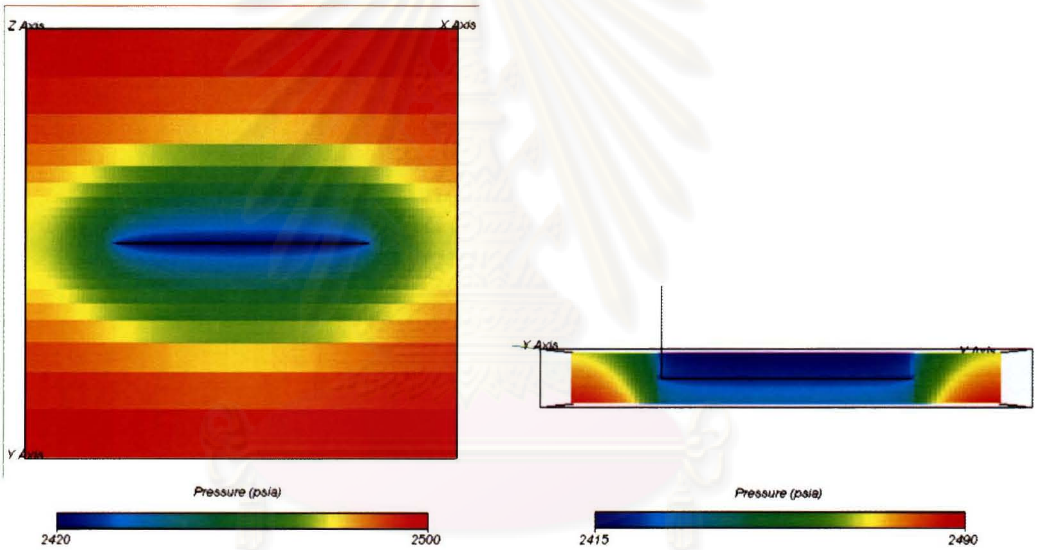

Figure 4.29: Pressure development for Case 1 with 60% partially penetrating well model (h=50ft, k_v/k_h=1).

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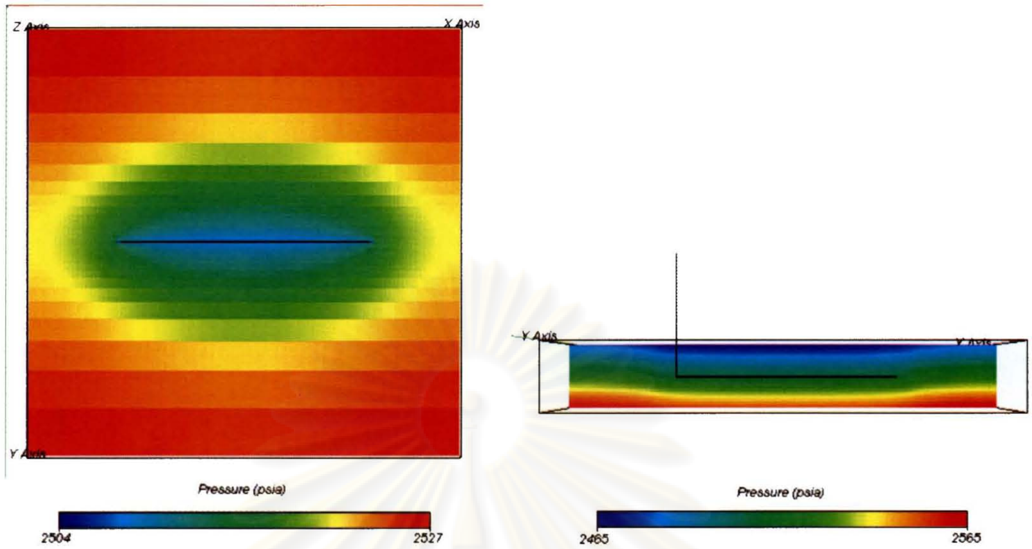

Figure 4.30: Pressure development for Case 2 with 60% partially penetrating well model (h=250ft, k_v/k_h=1).

Figure 4.29 and 4.30 illustrates pressure development for 60% partially penetrating well model with reservoir thicknesses of 50 and 250 ft, respectively. In the side view of Figure 4.29, there is more pressure differences between the edge and the middle of reservoir than the cases of h = 100 and 250 ft in Figure 4.28 and Figure 4.30. Figure 4.30 shows the pressure development is closely to linear flow.

We can presume that thin reservoir has strongly effect to the partial penetration in horizontal well compared with the thick reservoir. The thin reservoir has stronger effect from vertical flow and reduces the effect caused by partial penetration.

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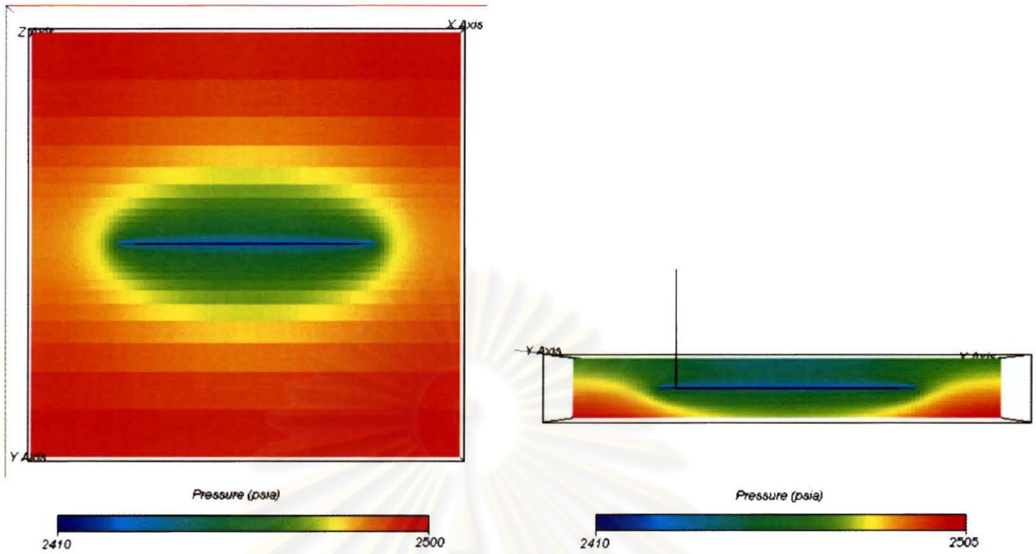

Figure 4.31: Pressure development for Case 3 with 60% partially penetrating well model

(h= 100ft, k_v/k_h=0.01).

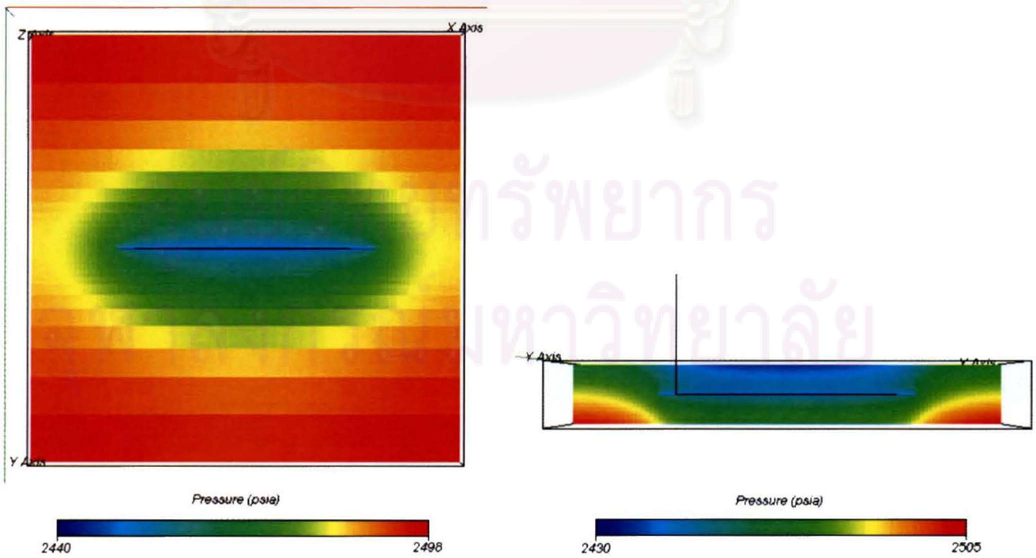

Figure 4.32: Pressure development for Case 4 with 60% partially penetrating well model

(h= 100ft, k_v/k_h=0.1).

Figure 4.31 and 4.32 illustrates pressure development for 60% partially penetrating well model with anisotropic ratio, k_v/k_h, of 0.01 and 0.1, respectively. As we can see, Figure 4.31 has pressure differences between the edge and the middle of reservoir than the base case (k_v/k_h= 1) in Figure 4.28. The results illustrate that the partial penetration skin factor is the reverse variation to the anisotropic ratio. A decrease in vertical permeability results in an increase in vertical-flow resistance and decrease in oil production rate, in order to maintain the production rate the pressure drop must be higher.

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4.1.3 Comparison of Partial Penetration Skins Determined from Analytical Equations, PROSPER software and Reservoir Simulation

From previous section, we determined partial penetration skin factor using different methods. The results from analytical equations and PROSPER software are then compared with those obtained from reservoir simulation. The coefficient of determination (R^2) of the 45 degree line is used to indicate the accuracy of each method compared to reservoir simulation. Figure 4.33 to Figure 4.37 show the comparison of partial penetration skin factors.

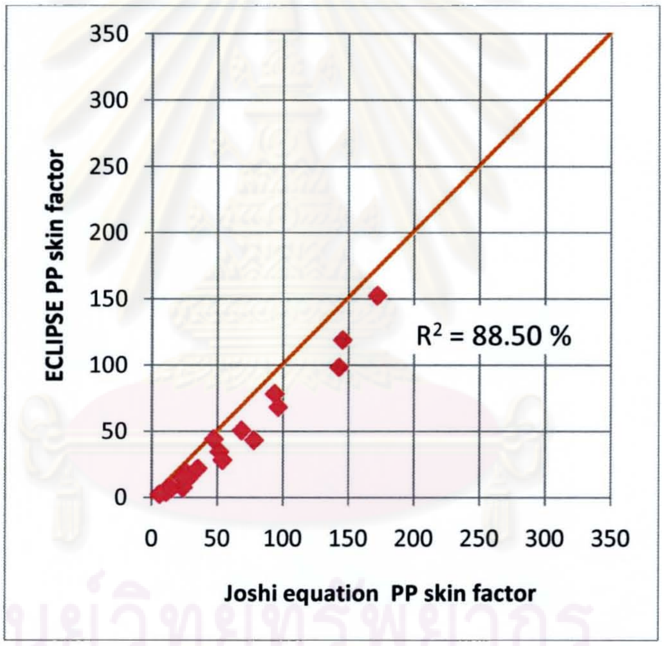

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*Figure 4.33: Comparison of partial penetration skin factors determined by Joshi equation and reservoir simulation.**

*Joshi equation cannot determine partial penetration skin factor for 20% penetration. Small value of anisotropic ratio (0.01) and small value of reservoir thickness (50 ft), cause the dimensionless length L_D to be less than 1, which is the minimum range of L_D.

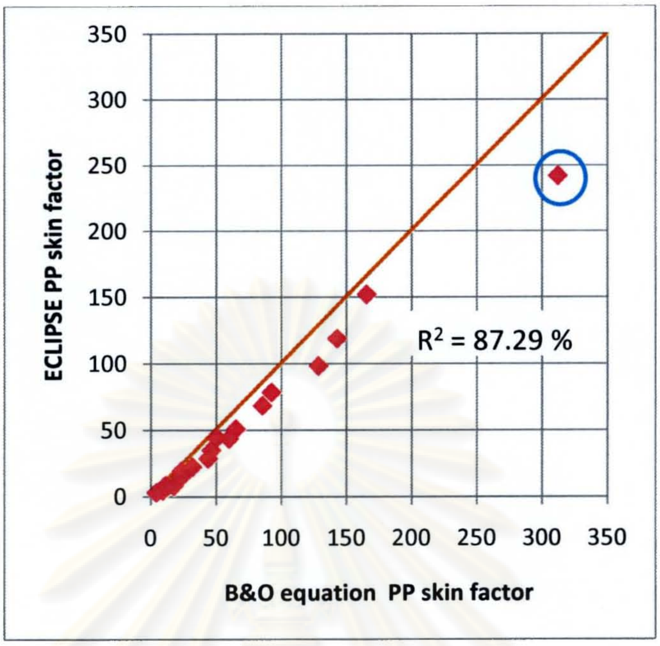

Figure 4.34: Comparison of partial penetration skin factors determined by Babu & Odeh analytical equation and reservoir simulation.

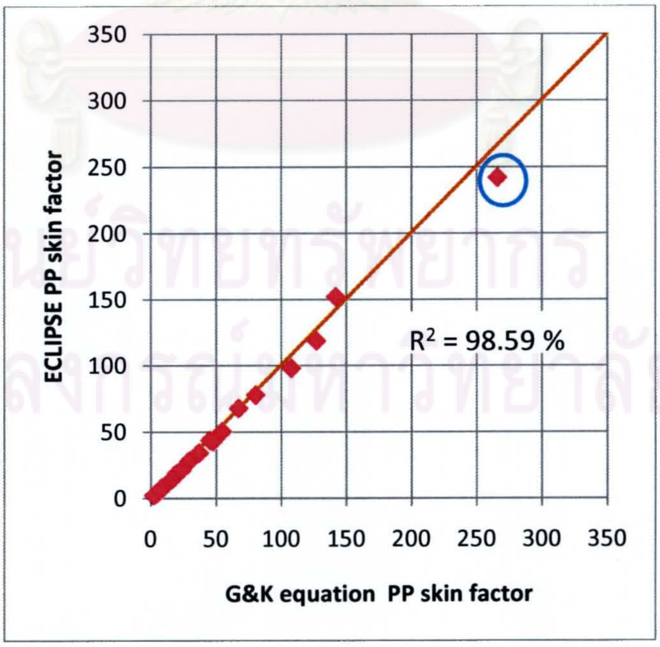

Figure 4.35: Comparison of partial penetration skin factors determined by Goode & Kuchuk analytical equation and reservoir simulation.

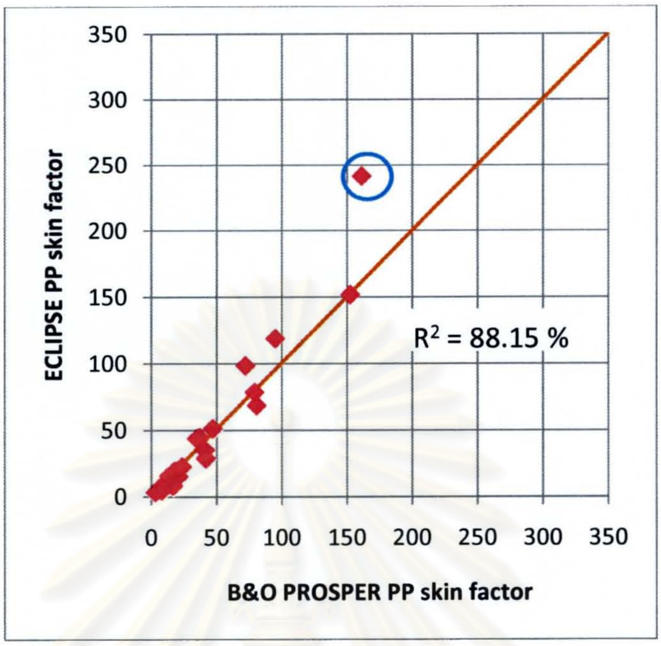

Figure 4.36: Comparison of partial penetration skin factors determined by Babu & Odeh available in PROSPER and reservoir simulation.

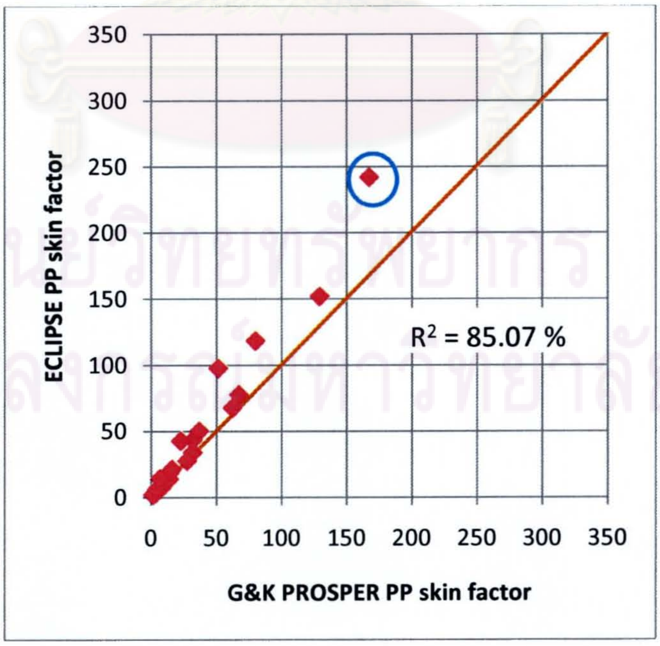

Figure 4.37: Comparison of partial penetration skin factors determined by Goode & Kuchuk available in PROSPER and reservoir simulation.

The values in the circle are the skin factor for the case of k_v/k_h = 0.01 with 20% partial penetration. Since these values are quite off the 45 degree line, we can presume that all analytical equations (Joshi *et al.*, Babu & Odeh, and Goode & Kuchuk) and PROSPER software have a limitation when anisotropic ratio is very low and the well penetrates a small portion of the reservoir.

Table 4.6 shows the summary of the coefficient of determination (R^2) of the 45 degree line. The results also show that the partial penetration skin factor determined by Goode & Kuchuk analytical equation has the highest R^2 value of 98.59%. Goode & Kuchuk equation available in PROSPER has the lowest R^2 value of 85.07%. We can conclude that the value of partial penetration skin factor obtained from Goode & Kuchuk equation is the most accurate while Goode & Kuchuk equation available in PROSPER is the least accurate when compared with those obtained from reservoir simulation.

Table 4.6 Summary of the coefficient of determination (R^2) of the 45 degree line.

Methods	Coefficient of determination (R^2)
Joshi equation	88.50 %
Babu & Odeh equation	87.29 %
Goode & Kuchuk equation	98.59 %
Babu & Odeh in PROSPER	88.15 %
Goode & Kuchuk in PROSPER	85.07 %

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4.2 Deviated Well Partial Penetration Skin

In order to determine the effect of partial penetration on the inflow performance, we can use the analytical equations or PROSPER software which is available for vertical and horizontal well. In this section, we determine the effect of partial penetration for deviated well which cannot be determined by PROSPER software. The main parameters for the base case in the previous section are also studied in the deviated well model.

In Section 4.1, we used ECLPSE 100 reservoir simulator to determine partial penetration skin for horizontal wells. In this section, we apply the same concept in order to determine the partial penetration skin factor for deviated well. A new reservoir model was set up in order to construct the deviated well model. In order to study the effect of partial penetration on deviated wells, various degrees of deviations were studied. We categorized different degrees of deviation into two kinds of deviated well. The first one is slightly deviated well, and another one is highly deviated well.

4.2.1 Determined of the Degree of Deviation for Studying

Since the zero degree of deviation is vertical well and the 90 degree of deviation is horizontal well, we selected the degree of 15, 30, 45, 60 and 75 for constructing the deviated well models. We defined the well deviated within this range as a slightly deviated well.

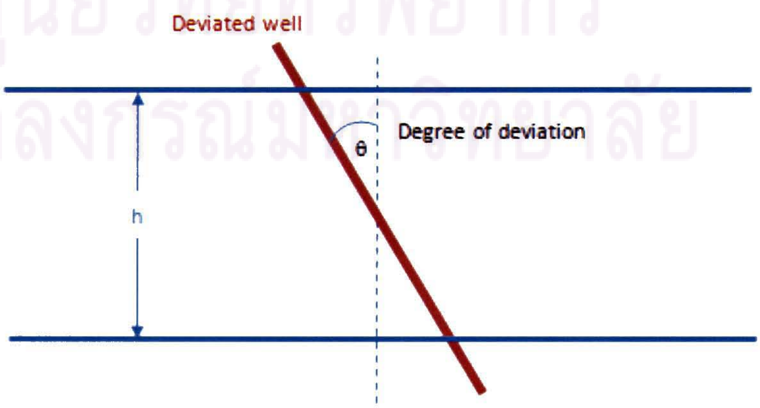

Figure 4.38: Configurations of a slightly deviated well.

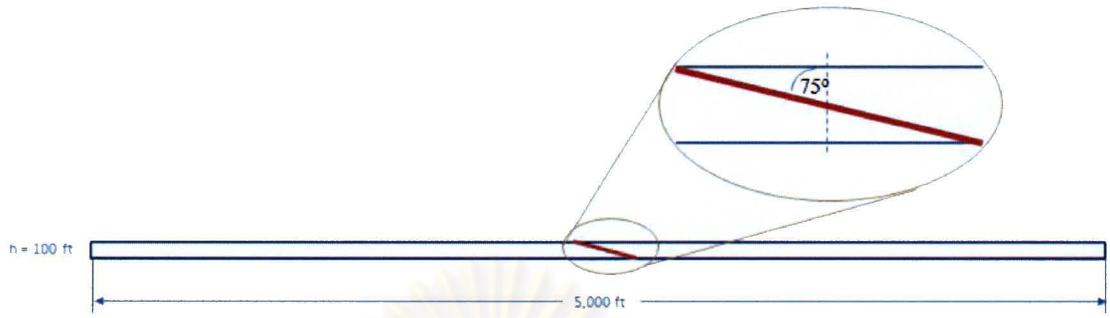

Figure 4.39: Configurations of the 75 degree deviated well in the 5,000 x 5,000 ft² and 100 ft thick reservoir

Figure 4.38 illustrates the configuration of a slightly deviated well. Figure 4.39 1illustrates the configuration of a slightly deviated well in a 5,000 × 5,000 ft^2 and 100 ft thick reservoir. We can see that the range of 0 – 75 degree of deviation covers only a little portion of the whole reservoir. A deviated well within the range of 75 – 90 degree is defined as a highly deviated well. In order to study this range, we define the degree of deviation base on the reservoir thickness and length. The length of the deviated well projecting on the X-axis is defined as L_x and the degree of deviation, θ is determined by an arctangent of L_x/h. L_x of 1000, 2000, 3000, 4000 and 5000 ft are selected in order to study the effect of deviation. Figure 4.40 illustrates the configurations of the highly deviated well and the definition of L_x.

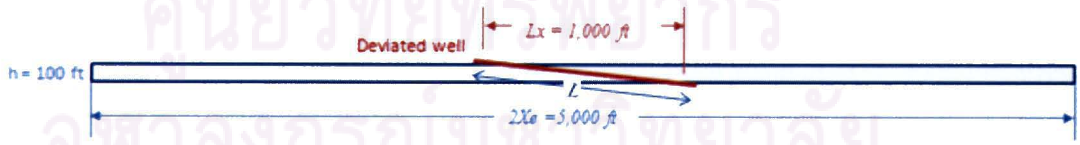

Figure 4.40: Configurations of the highly deviated well with L_x = 1,000 ft in the 5,000 x 5,000 ft² and 100 ft thick reservoir.

4.2.2 Partial Penetration Skin for Slightly Deviated Well

Deviated wells with the deviations of 15, 30, 45, 60 and 75 degree are modeled in a reservoir with the same properties as the base case in Section 4.1 by using ECLIPSE 100 reservoir simulator. The partial penetration skin factors for different degrees of deviation were determined and compared with the partial penetration skin factor for the vertical well.

Reservoir Model for Slightly Deviated Well

The reservoir with a drainage area of 5,000 x 5,000 ft used in Section 4.1 is used as a reservoir model again. The number of grid is 100 x 51 x 40 blocks for X, Y and Z direction, respectively. The dimension of deviated well was calculated. Two middle blocks in the X direction were modeled to cover the range that the deviated well go through. Then, the dimension of the remaining X grids are equally divided. The Y grid block dimensions are exponentially increased away from both sides of the deviated well. The thickness of 100 ft is equally distributed for 40 blocks. The 3-D view of the actual simulation grid is illustrated in Figure 4.41. The same reservoir properties and production used in the base case in Section 4.1 are used.

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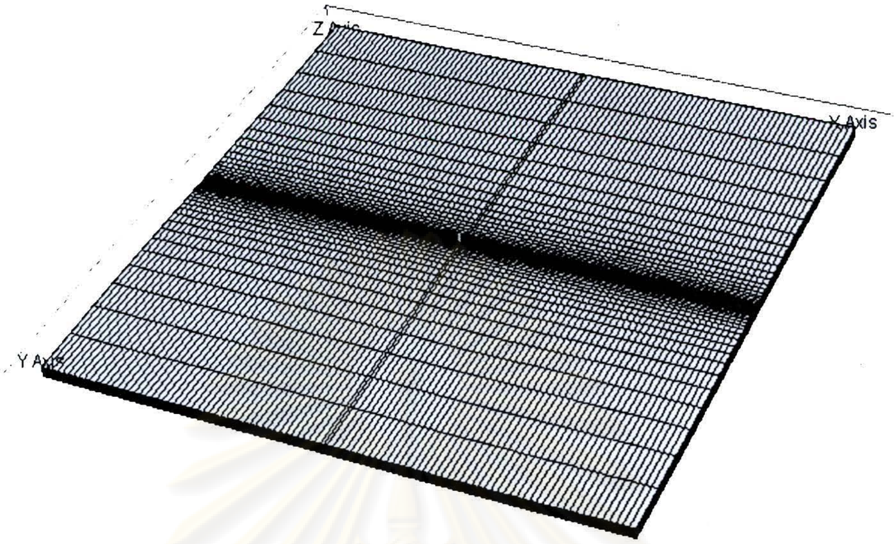

Figure 4.41: 3-D view of the actual simulation grid for slightly deviated well.

Slightly Deviated Well Model

The two middle blocks in the X direction cover the whole length of the slightly deviated well projecting on the X axis. Then, the X dimensions of these blocks depend on the degree of deviation. For example, the length of 30-degree of deviated well projecting on the X axis of the 100 ft thick reservoir is 57.75 ft (= $100 * \tan 30^o$) as shown in Figure 4.42. Then, the X dimension of each block is 28.87 ft. In order to place the deviated well in these two blocks, these two blocks are locally refined into 20 blocks using Local Grid Refinement (LGR) method which is available in ECLIPSE 100. Since we cannot model the deviated well as a straight line, then the deviated well is placed as a zigzag line into the refined grids [17] in order to represent the completion of deviated well. Figure 4.43 illustrates the deviated well model. The reference line is an indicator of the center of the reservoir and a marker for places the well and deviates to both sides. The fluid properties are the same as the base case in Section 4.1.

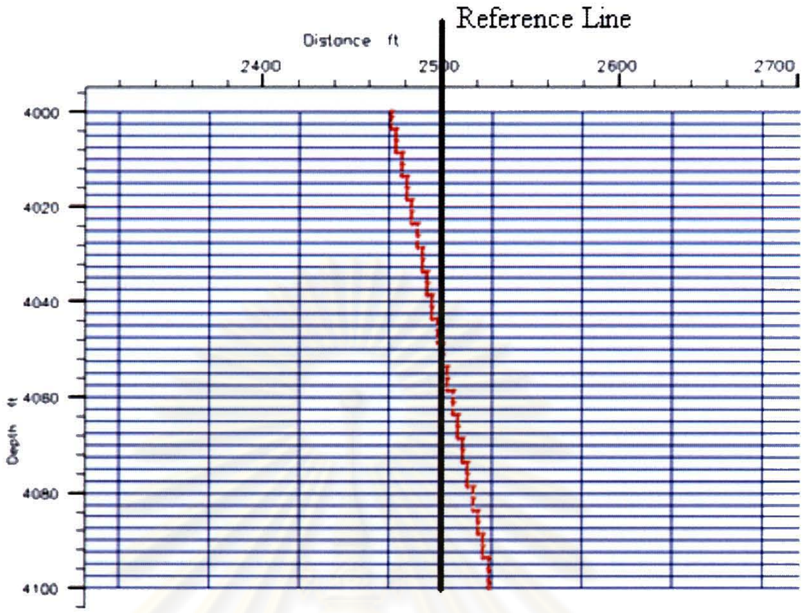

Figure 4.42: XZ-plane of the 100 ft thickness reservoir for 30 degree deviated well (without LGR).

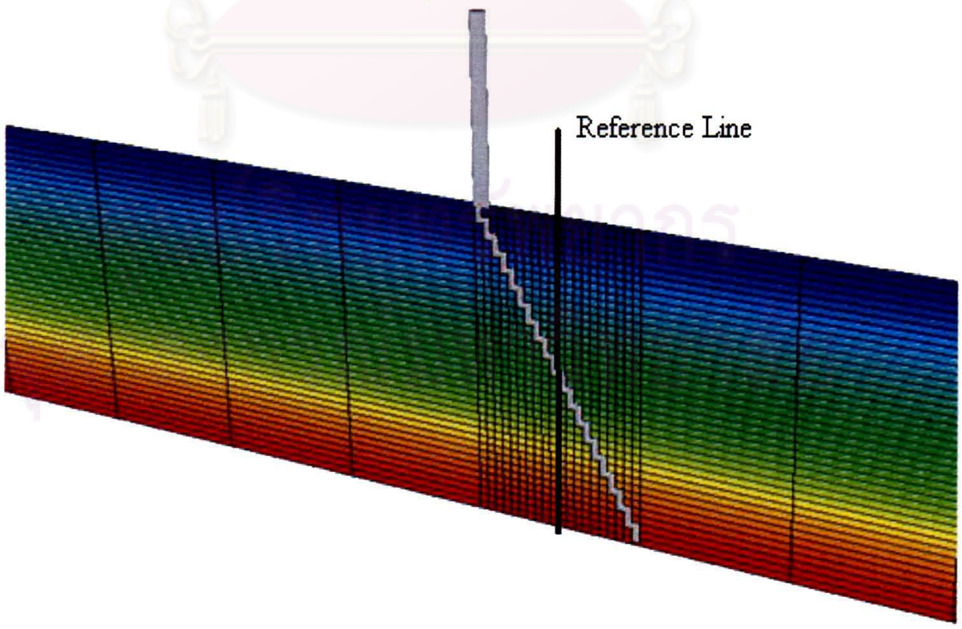

Figure 4.43: Well model for 30 degree of fully penetrating deviated well.

We can determine the partial penetration skin factor for slightly deviated by (1) matching the pressure histories for the fully penetrating deviated well with skin with that for the partially penetrating deviated well as same as the method used for horizontal well (2) determine the total skin factor (s_t) then subtracting by the skin due to deviation (s_θ) to get the partial penetration skin factor (s_{pp}). Figure 4.44 show the flow chart to determine partial penetration skin factor by matching the pressure histories. Figure 4.45 show the flow chart to determine partial penetration skin factor by calculating total skin factor.

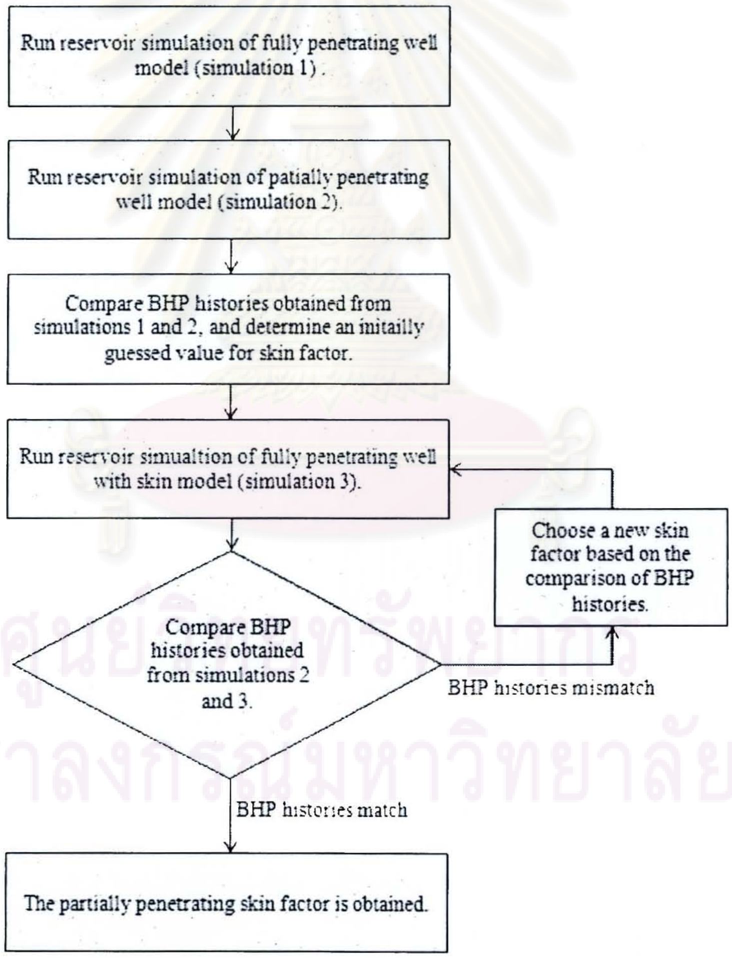

Figure 4.44: Determination of partial penetration skin factor from matching pressure histories.

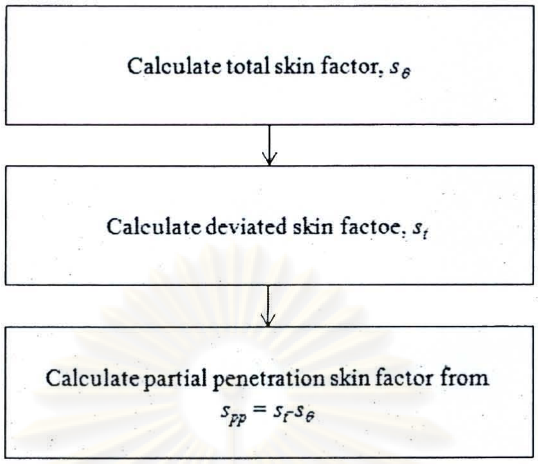

Figure 4.45: Determination of partial penetration skin factor from total skin factor.

Case study for simulation

The reservoir thickness used in this study is 100 ft. Different well configurations are studied in order to determine the partial penetration skin factor for different degrees of deviation and percentages of partial penetration. Table 4.7 shows the general well dimensions for this study. Figure 4.46 illustrates a skin factor for a 60% partial penetrating well at 30 degree deviation.

Table 4.7: General well dimensions for case studies with reservoir thickness 100 ft.

	Partially penetrating well length, L (ft)				
Degree of deviation, θ	Fully	20%	40%	60%	80%
0°	100	20	40	60	80
15°	103.53	100.14	100.57	101.28	102.27
30°	115.47	100.66	102.63	105.83	110.15
45°	141.42	101.98	107.70	116.62	128.06
60°	200.00	105.83	121.66	144.22	170.88
75°	386.37	124.78	179.68	245.24	314.87

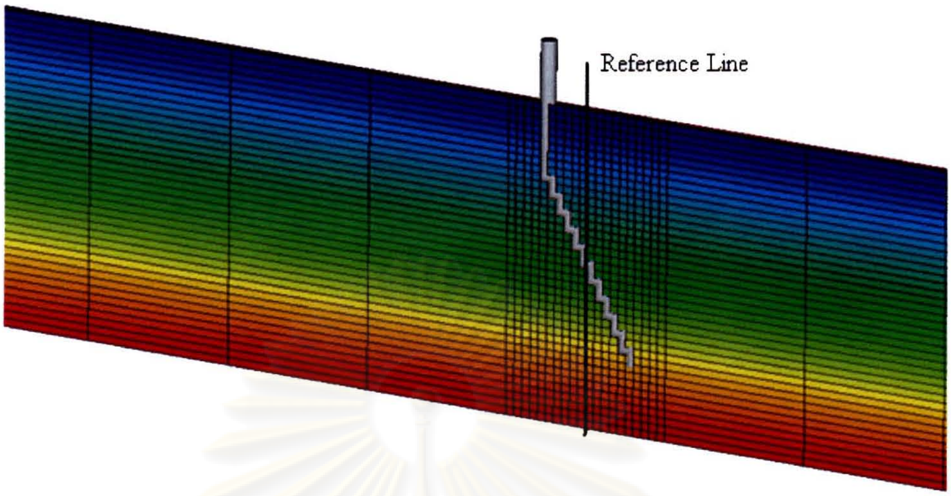

Figure 4.46: Well model for 30 degree of 60% partially penetrating deviated well.

Determination of Partial Penetration Skin Factor

As mentioned in Chapter 3, there are 3 equations for calculating the skin due to the deviated well, Cinco *et al.*, Besson, and Roger & Economides. We also can determine deviated skin factors using ECLIPSE 100 by obtaining the pressure drop difference between fully penetrating vertical well and the deviated well for different degrees of deviation. Figure 4.47 shows the deviated skin factor determined by different methods as a function of degree.

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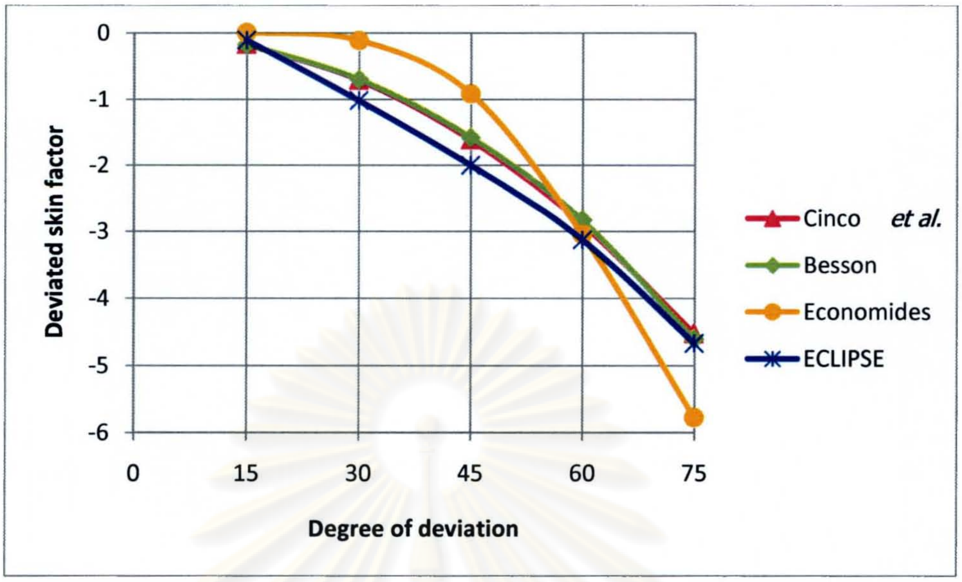

Figure 4.47: Deviated skin factor by different methods.

All methods give the results that follow the same trend. The results from Cinco and Besson are close and look like the same line. Since the result from ECLIPSE is in the same range as those from the equations, the accuracy of skin factor determination using the slightly deviated well model is acceptable. This deviated skin factor relates to the inflow performance of the vertical well. We can apply this skin factor to the IPR equation of vertical well in order to determine the productivity.

Now we obtain the skin factor for the deviated well which fully penetrates the whole reservoir thickness. The next step is to study the effect of partial penetration on the deviated well. In order to determine the partial penetration skin factor, we determine the total skin factor (s_t) including the skin due to deviation (s_θ) and partial penetration (s_{pp}) then subtracting by the deviated skin factor (s_θ) obtained from ECLIPSE.

$$s_t = s_\theta + s_{pp}$$

then

$$s_{pp} = s_t - s_\theta$$

Figure 4.48 shows the total skin factors determined by ECLIPSE for different degrees of deviation and percent of partial penetration. The deviated skin line represents the fully penetrating well or no partial penetration skin. After subtracting the total skin lines by the deviated skin line, we get the partial penetration skin plot as shown in Figure 4.49. We can see that the partial penetration skin decreases when the degree of deviation increases.

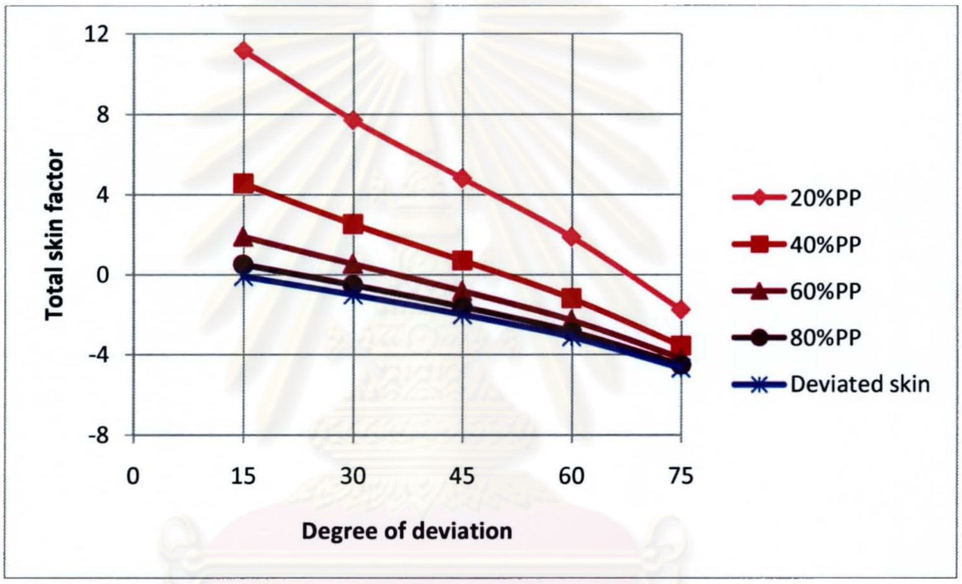

Figure 4.48: Total skin factors obtained from ECLIPSE.

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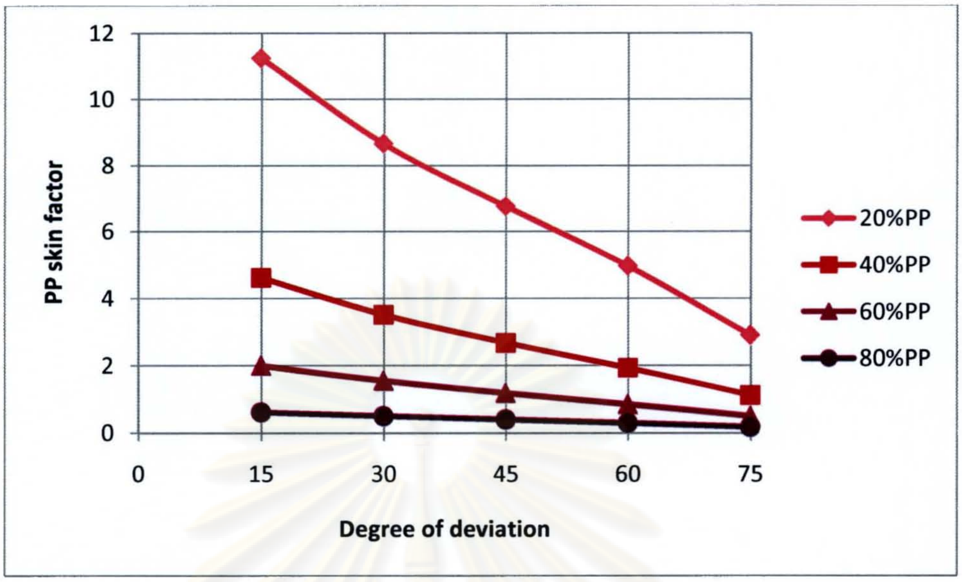

Figure 4.49 Partial penetration skin factors obtained by subtracting the total skin factor by the deviated skin factor.

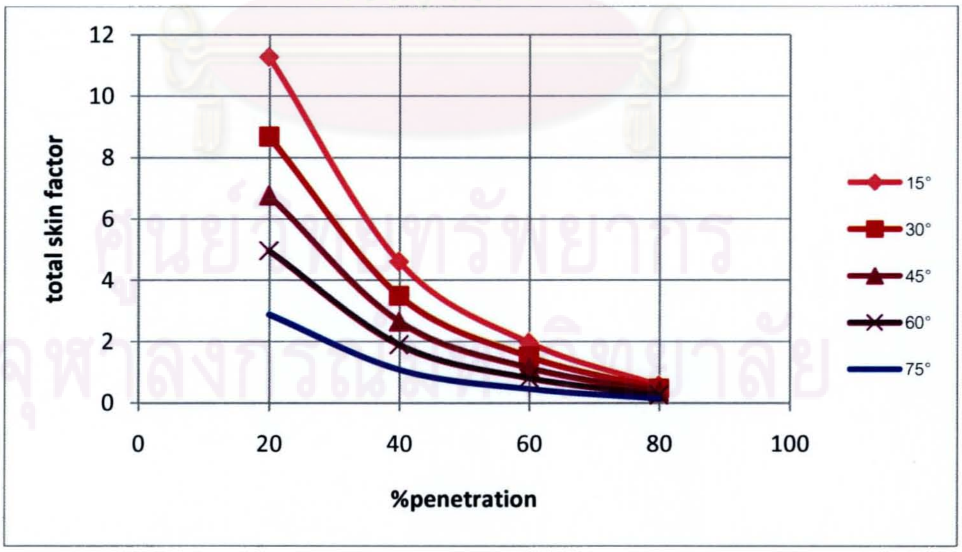

Figure 4.50: Comparison of partial penetration skin factors from different degree of deviation.

Figure 4.50 illustrate the comparison of partial penetration skin factor from different degree of deviation. The values is equally for both methods, (1) matching the pressure (2) determine the total skin factor.

4.2.3 Partial Penetration Skin for Highly Deviated Well

For a slightly deviated well, the partial penetration skin factor can be determined by the total skin factor subtracted by the deviated skin factor $(s_{pp} = s_t - s_\theta)$ which can be determined using analytical equations. However, there is no analytical equation to determine the deviated skin where $75° < \theta < 90°$. In order to determine the effect of partial penetration on a highly deviated well, we use the method similar to that used in Section 4.1. The highly deviated well model is different from the slightly deviated well model. We define the degree of deviation as the well length in the X-direction (L_x) as shown in Figure 4.40. The deviated well with L_x of 1000, 2000, 3000, 4000 and 5000 ft were modeled in the reservoirs with the same properties as used in Section 4.1 by using ECLIPSE 100. Then, the partial penetration skin factors for different L_x were determined.

Reservoir Model for Highly Deviated Well

The reservoir with a drainage area of 5,000 x 5,000 ft used in Section 4.1 is used as reservoir model again. The number of grid is 100 x 51 x 40 blocks for X, Y and Z direction, respectively. The X grids are equally divided for 100 blocks. The Y grid block dimensions are exponentially increased away from both sides of the deviated well. The Z grid block dimensions are equally distributed for 40 blocks. The 3-D view of the actual simulation grid is illustrated in Figure 4.51. The same reservoir properties and production used in the base case in Section 4.1 are used.

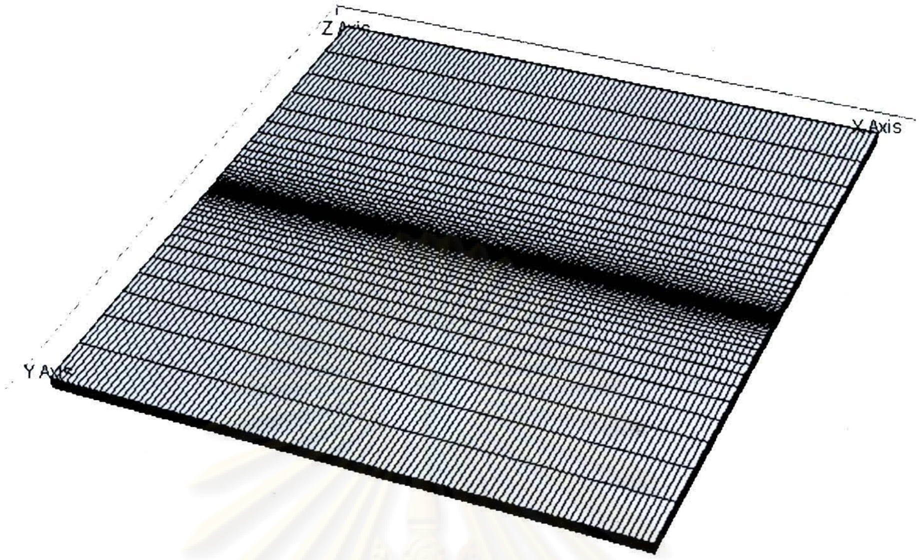

Figure 4.51: Reservoir model for a highly deviated well.

Highly Deviated Well Model

Since we cannot model the deviated well as a straight line, then the deviated well is placed as a zigzag line into the reservoir model in order to represent the completion of deviated well. Figure 4.52 illustrates the deviated well model. The fluid properties are the same as those in the base case in Section 4.1.

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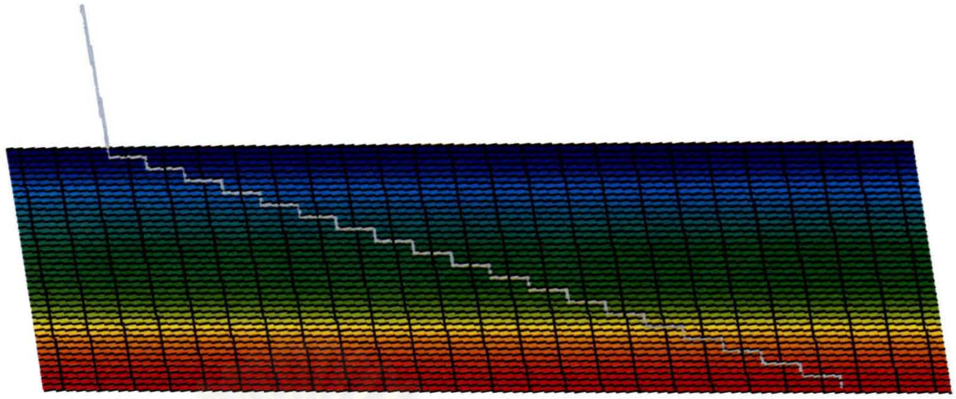

Figure 4.52: A highly deviated well model for $\mathbf{L_x}$ *= 1000 ft.*

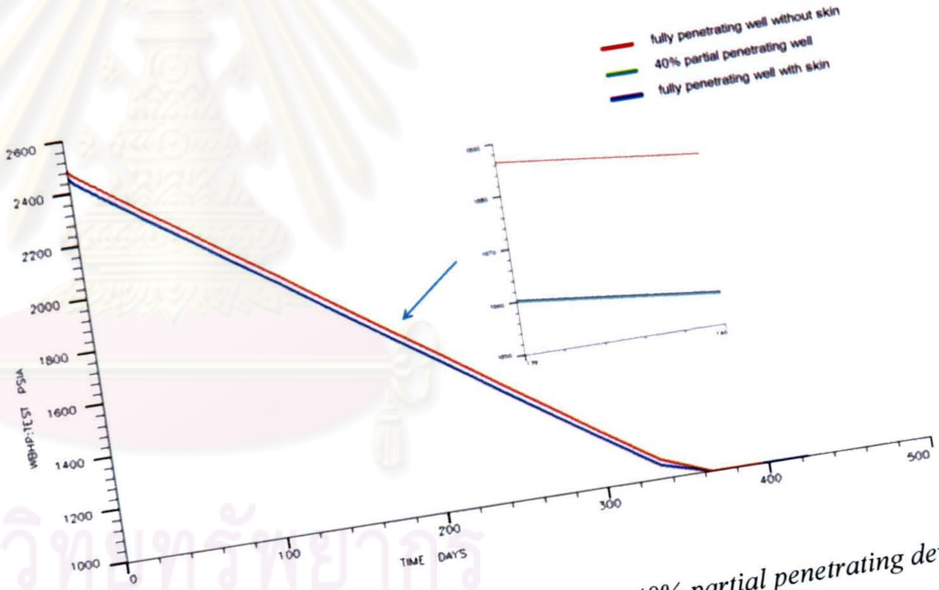

Figure 4.53: Comparison of pressure histories between 40% partial penetrating deviated well, fully penetrating deviated well with skin, and fully penetrating deviated well without skin for $\mathbf{L_x}$ *= 5000 ft.*

The bottom hole pressure history of the fully penetrating deviated well with skin is matched with the bottom hole pressure history of the partially penetrating deviated well as shown in Figure 4.53. The value of skin factor causing these pressure histories to be matched is the partial penetration skin factor for the deviated well. Figure 4.54 show the flow chart to determine partial penetration skin factor by matching the pressure histories.

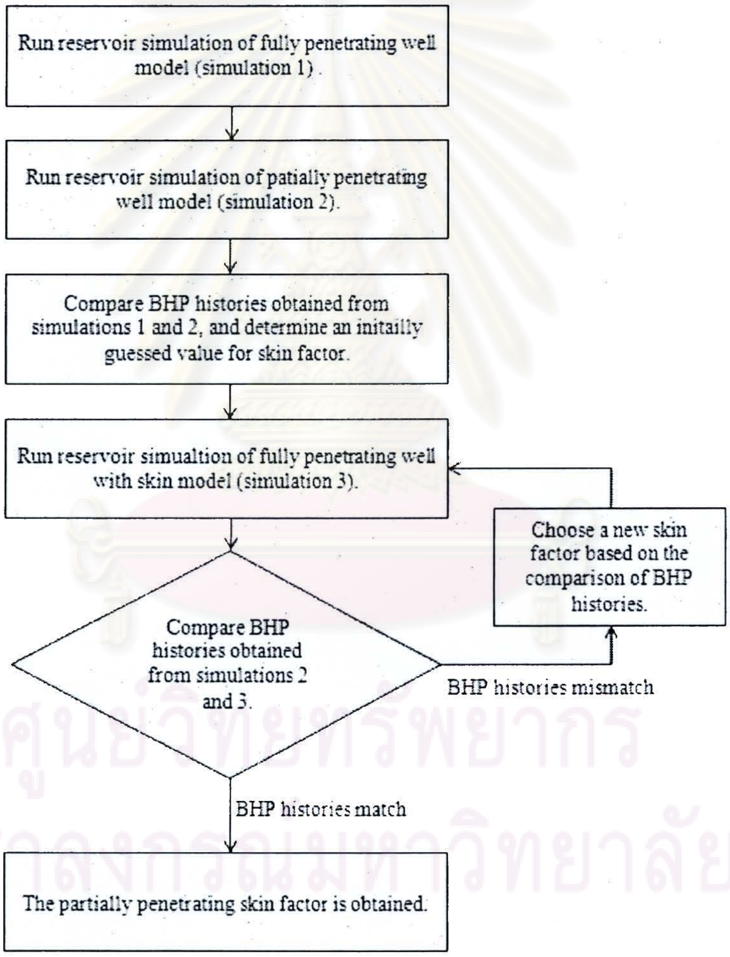

Figure 4.54: Determination of partial penetration skin factor from matching pressure histories.

Case Study for Simulation

The effect of partial penetration on the highly deviated well was determined for different conditions. Different well configurations and reservoir anisotropies were studied in order to determine partial penetration skin factor for different degree of deviations and percentage of partial penetration. The degree of deviation and well length can be determined from the thickness and L_x of the reservoir. Table 4.8 and 4.9 show the well length and the degree of deviation for each L_x and reservoir thickness.

Table 4.8: Well length for each L_x and reservoir thickness.

L_x, ft	Well length, ft		
	h = 50 ft	h = 100 ft	h = 250 ft
1000	1001.25	1004.99	1030.78
2000	2000.62	2002.50	2015.56
3000	3000.42	3001.67	3010.40
4000	4000.31	4001.25	4007.80
5000	5000.25	5001.00	5006.25

Table 4.9: Degree of deviation for each L_x and reservoir thickness.

L_x, ft	Degree of deviation, θ		
	h = 50 ft	h = 100 ft	h = 250 ft
1000	87.14	84.29	75.96
2000	88.57	87.14	82.87
3000	89.05	88.09	85.24
4000	89.28	88.57	86.42
5000	89.43	88.85	87.14

Results from Case Study

The results of all cases are shown in Figures 4.55 to 4.60 as a comparison for the same thickness. The results are shown as the partial penetration skin factor (PP skin factor) versus the percentage of the horizontal well partially penetrating into the reservoir (%penetration).

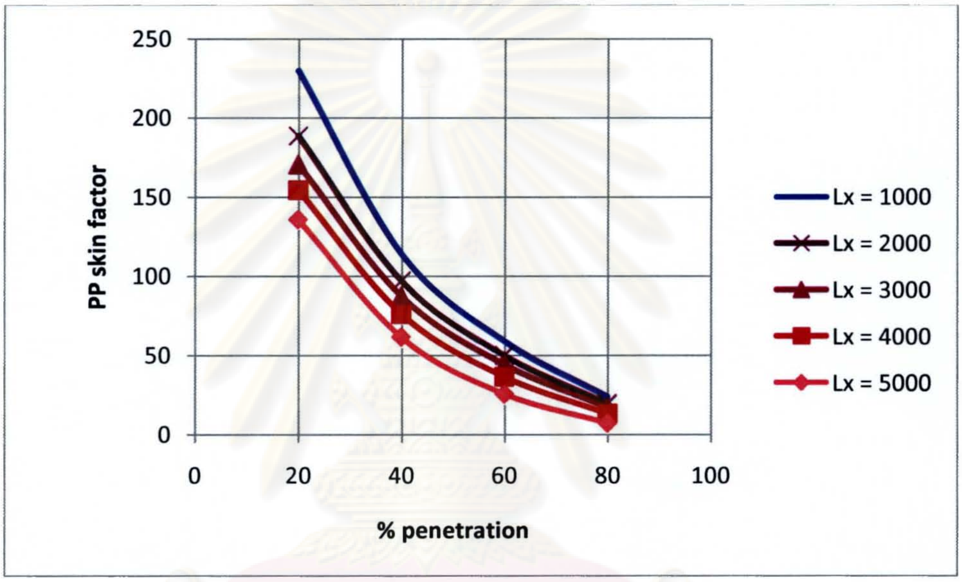

Figure 4.55: Partial penetration skin factor for different L_x

(reservoir thickness of 50 ft).

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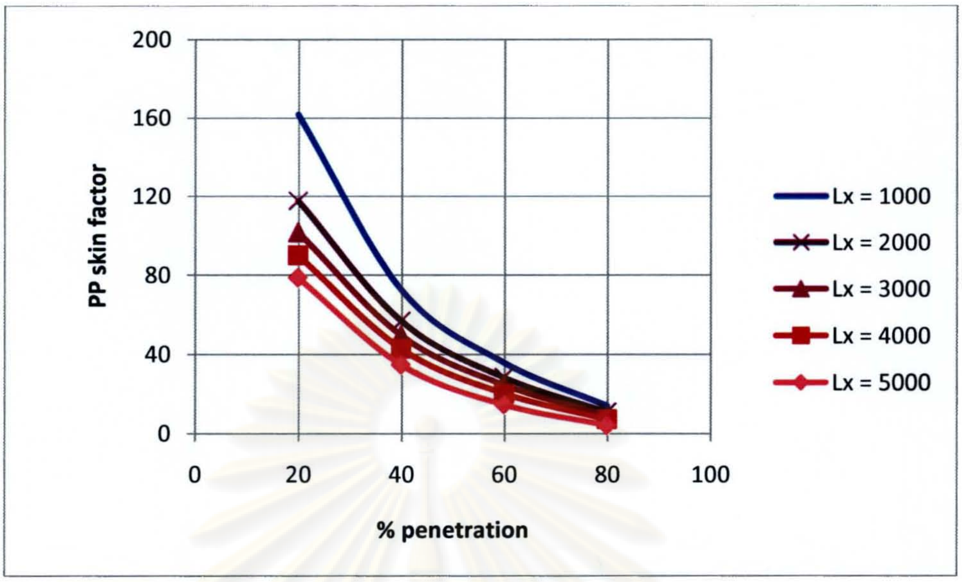

Figure 4.56: Partial penetration skin factor for different L_x

(reservoir thickness of 100 ft).

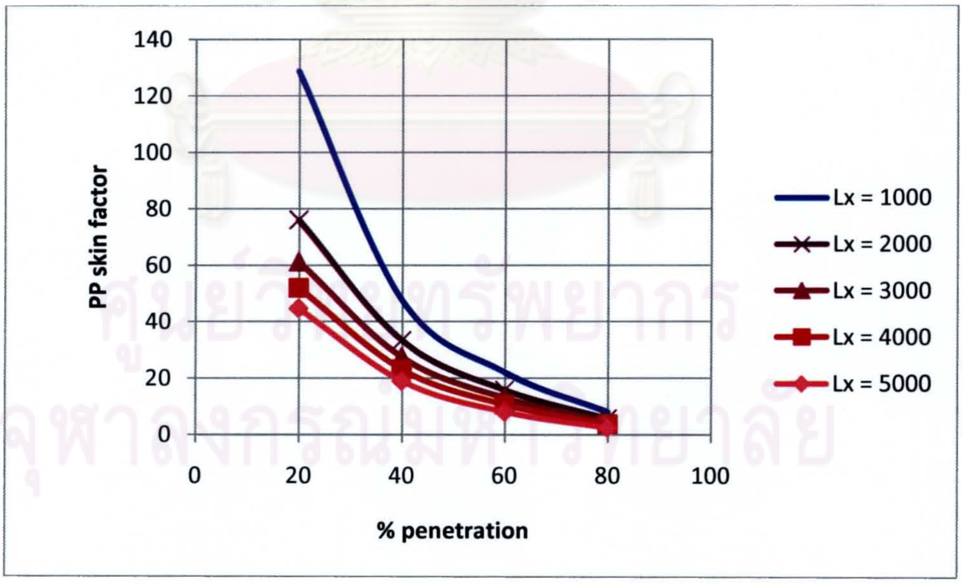

Figure 4.57: Partial penetration skin factor for different L_x

(reservoir thickness of 250 ft).

From Figures 4.55 to 4.57, the results show that the relationships between partial penetration skin factor and percent penetration follows the same trend. The value of partial penetration skin factor decreases as the deviated well penetrates longer into the reservoir in the X-direction.

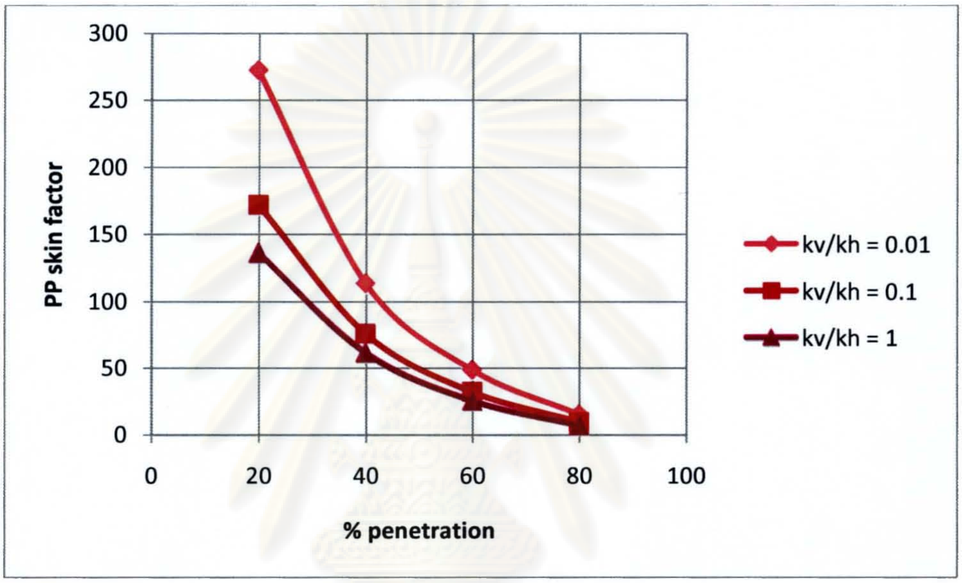

Figure 4.58: Partial penetration skin factor for different k_v/k_h

(reservoir thickness of 50 ft and L_x *= 5,000 ft).*

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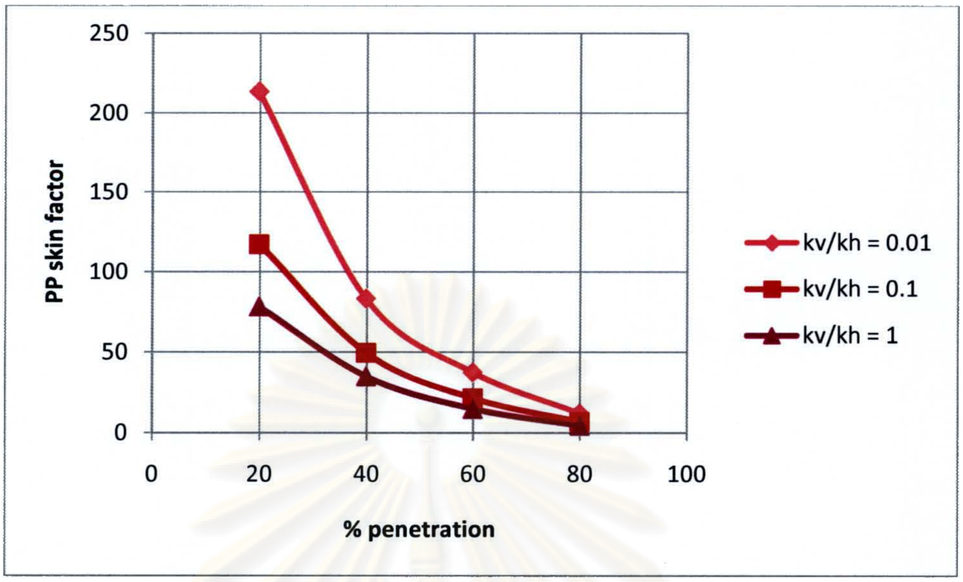

Figure 4.59: Partial penetration skin factor for different k_v/k_h

(reservoir thickness of 100 ft and L_x *= 5,000 ft).*

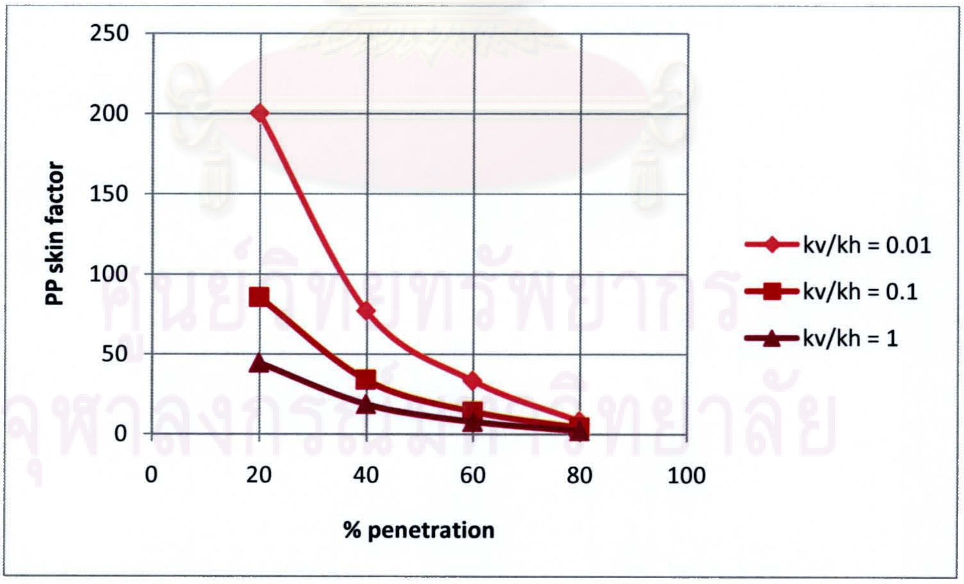

Figure 4.60: Partial penetration skin factor for different k_v/k_h

(reservoir thickness of 250 ft and L_x *= 5,000 ft).*

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Figures 4.58 to 4.60 compare partial penetration skin for reservoir anisotropic ratio of 0.01, 0.1 and 1. The results show that the partial penetration skin factor is a reverse variation to the anisotropic ratio.

As seen in Figure 4.59, the case with reservoir thickness of 100 ft and L_x of 5,000 ft gives the result similar to the result from the horizontal well model as shown in Figure 4.26 in Section 4.1 because the well trajectory of a highly deviated well (88.85 degree) is close to that of a horizontal well. The partial skin factors for horizontal well are a bit higher than those of the deviated well due to less in exposure into the reservoir than the horizontal well. The comparison between the deviated well with the horizontal well is shown in Figures 4.61 to 4.63.

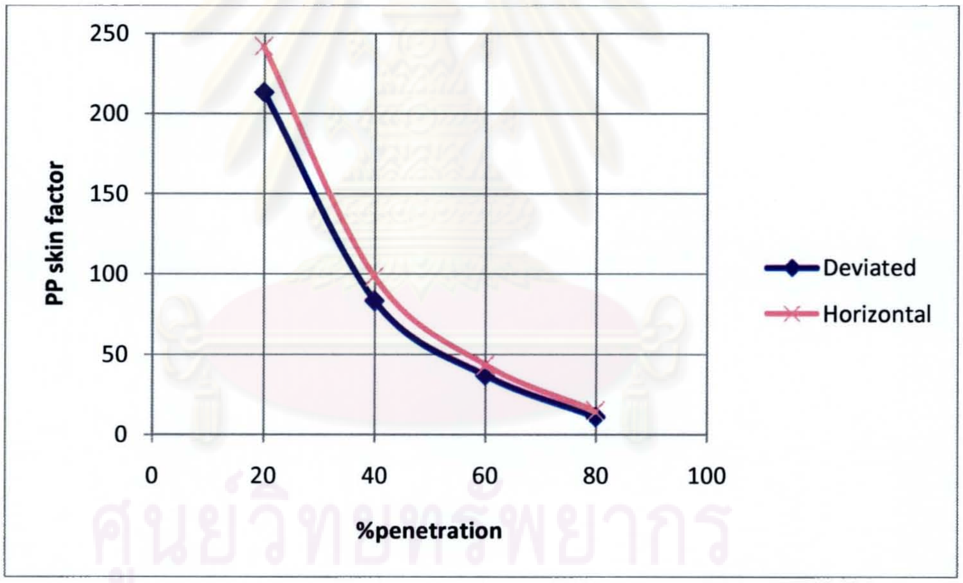

Figure 4.61: Comparison between deviated and horizontal wells for k_v/k_h = 0.01 (100 ft thick reservoir).

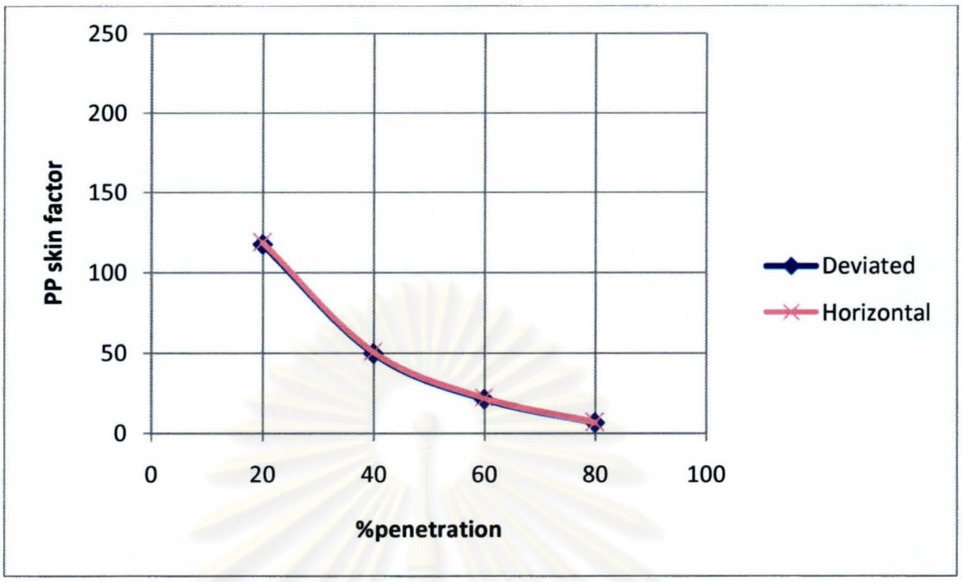

Figure 4.62: Comparison between deviated and horizontal wells for k_v/k_h= 0.1

(100 ft thick reservoir).

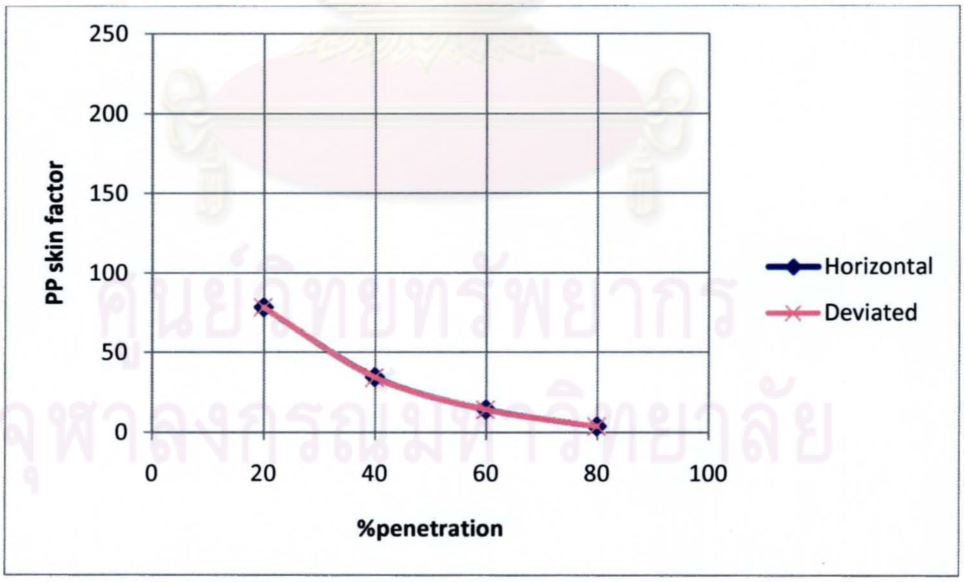

Figure 4.63: Comparison between deviated and horizontal wells for k_v/k_h= 1

(100 ft thick reservoir).

Figures 4.61 to 4.63 show that the partial skin factors of the deviated and horizontal well are very close for k_v/k_h equal to 0.1 and 1. However, for k_v/k_h = 0.01 the partial penetration skin factors of the deviated well are less than those of the horizontal well. For deviated well, fluid can flow into the wellbore in horizontal plane even when the vertical permeability is 0. So, in the case with a very low anisotropic ratio, i.e. k_v/k_h= 0.01, with small portion of partially penetrated into the reservoir, the deviated well shows less partial penetration skin factor than the horizontal well.

4.2.4 Comparison between Partial Penetration Skin from Highly Deviated and Horizontal Well

In Section 4.2.3, we see that the partial penetration skin factor from a deviated well is quite similarly to that obtained from a horizontal well. In this section, we compare the difference between the two models. The horizontal well models for different L_x were simulated in order to obtain their partial penetration skin factors. Figures 4.64 to 4.78 compare partial penetration skin factors for a horizontal well and a highly deviated well for different L_x and reservoir thickness.

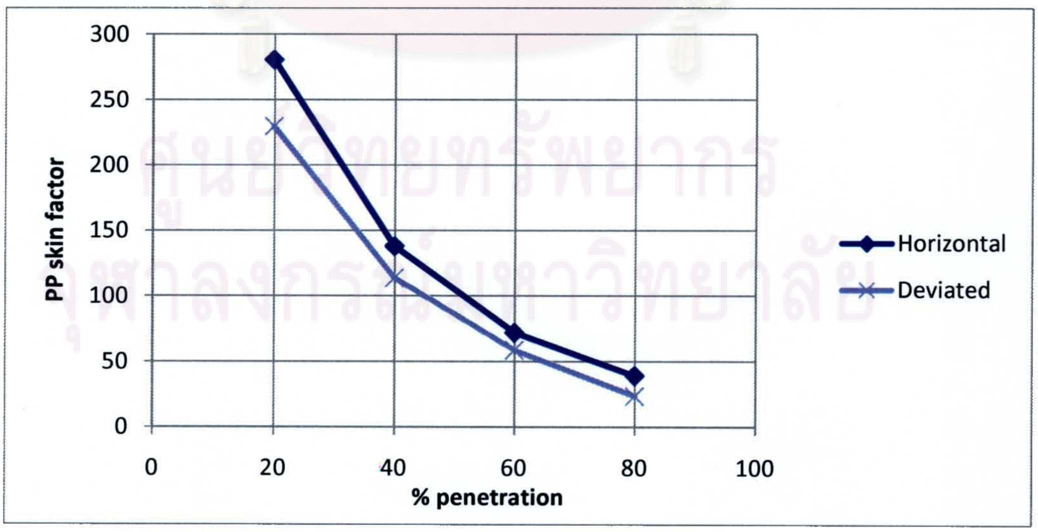

Figure 4.64: Comparison of partial penetration skin factor between for horizontal and the highly deviated wells for L_x = 1,000 ft and reservoir thickness of 50 ft.

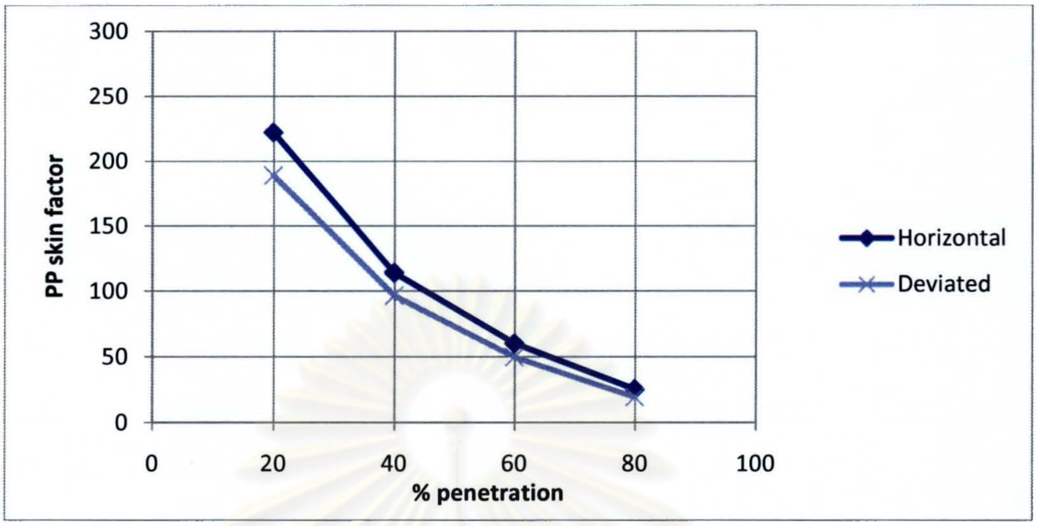

Figure 4.65: Comparison of partial penetration skin factor between for horizontal and the highly deviated wells for L_x = 2,000 ft and reservoir thickness of 50 ft.

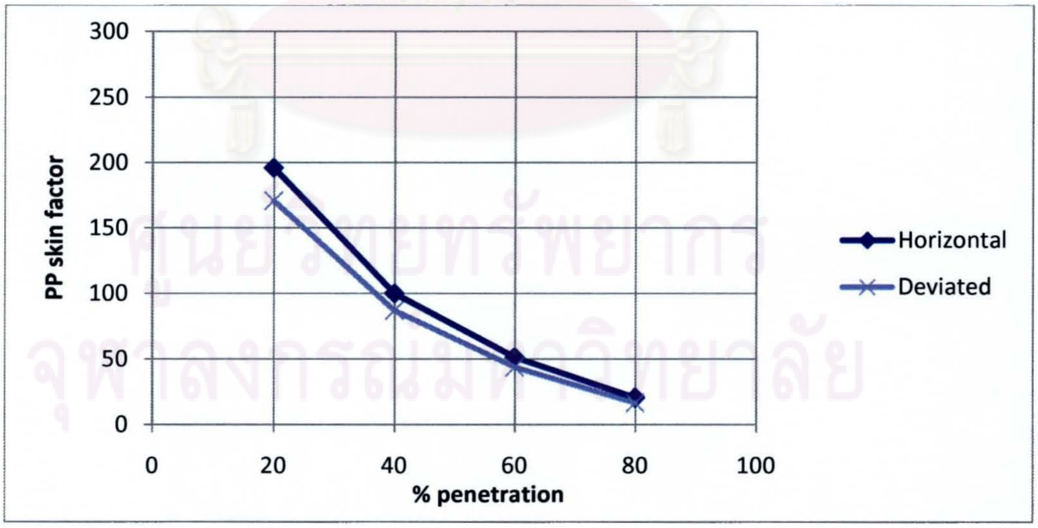

Figure 4.66: Comparison of partial penetration skin factor between for horizontal and the highly deviated wells for L_x = 3,000 ft and reservoir thickness of 50 ft.

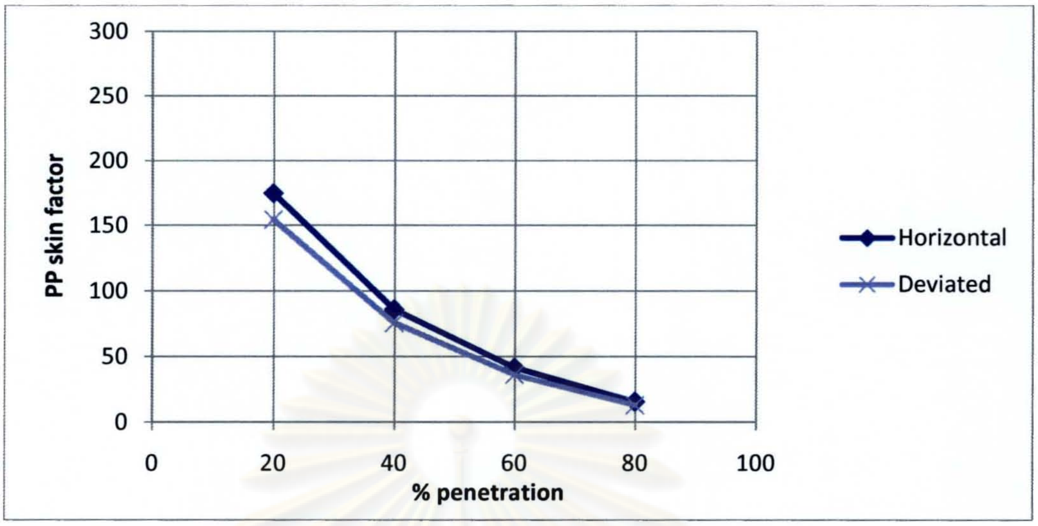

Figure 4.67: Comparison of partial penetration skin factor between for horizontal and the highly deviated wells for L_x = 4,000 ft and reservoir thickness of 50 ft.

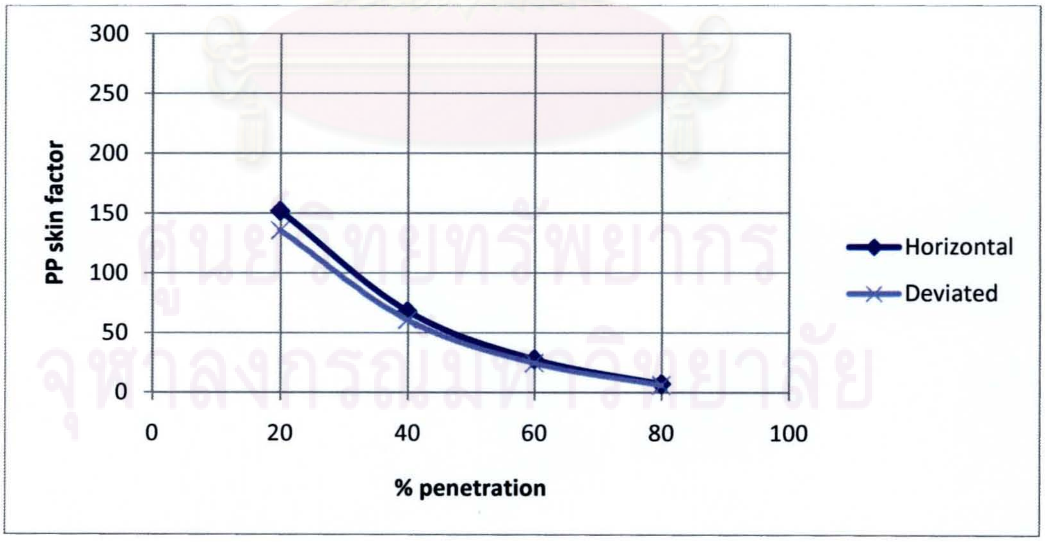

Figure 4.68: Comparison of partial penetration skin factor between for horizontal and the highly deviated wells for L_x = 5,000 ft and reservoir thickness of 50 ft.

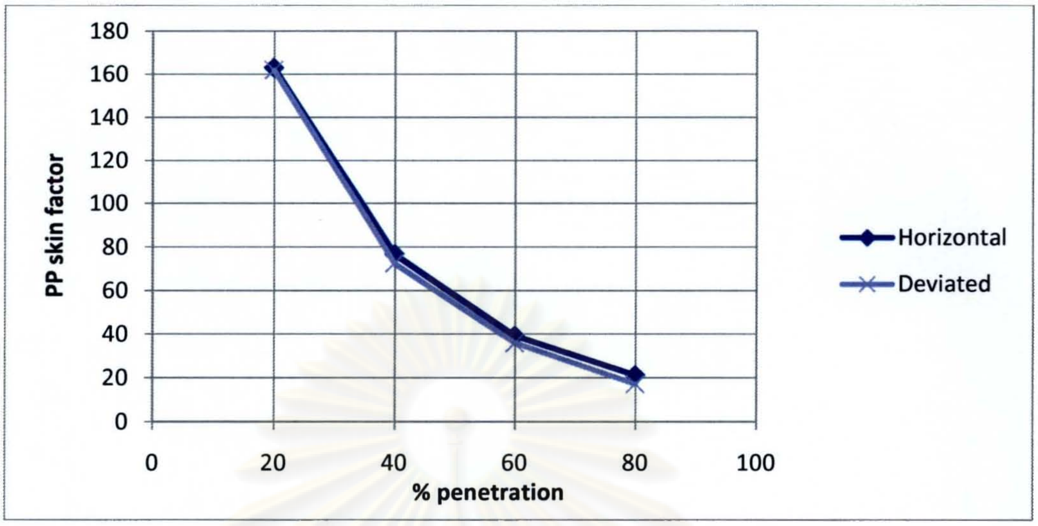

Figure 4.69: Comparison of partial penetration skin factor between for horizontal and the highly deviated wells for L_x = 1,000 ft and reservoir thickness of 100 ft.

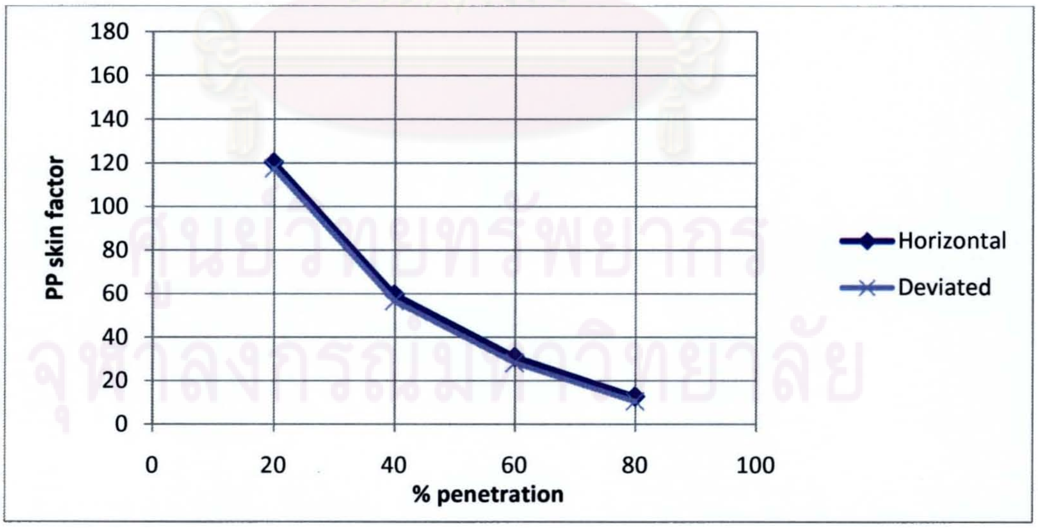

Figure 4.70: Comparison of partial penetration skin factor between for horizontal and the highly deviated wells for L_x = 2,000 ft and reservoir thickness of 100 ft.

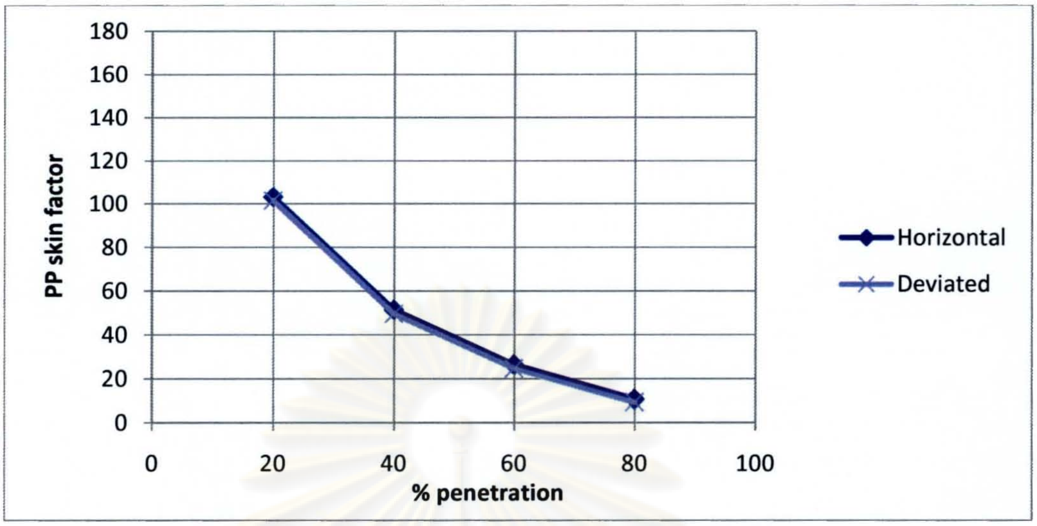

Figure 4.71: Comparison of partial penetration skin factor between for horizontal and the highly deviated wells for L_x = 3,000 ft and reservoir thickness of 100 ft.

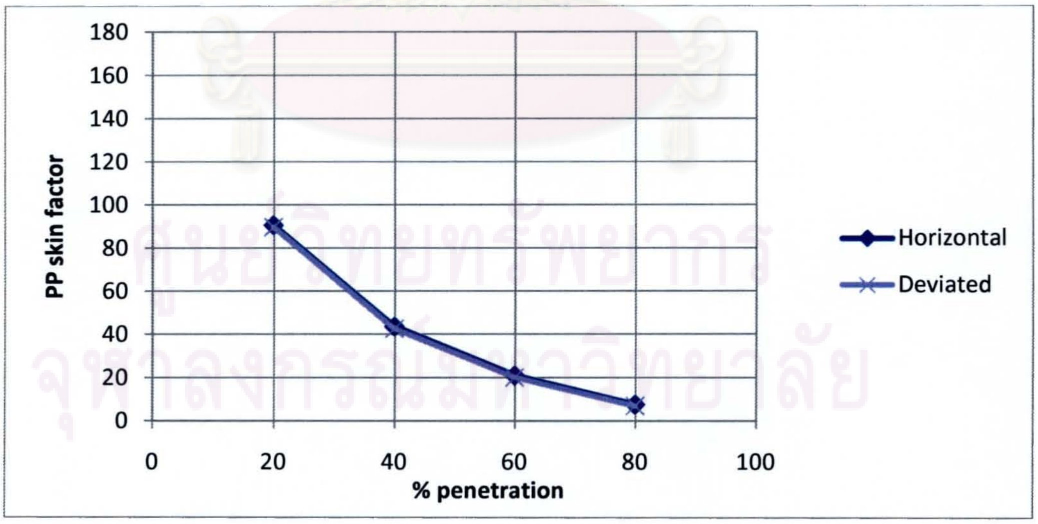

Figure 4.72: Comparison of partial penetration skin factor between for horizontal and the highly deviated wells for L_x = 4,000 ft and reservoir thickness of 100 ft.

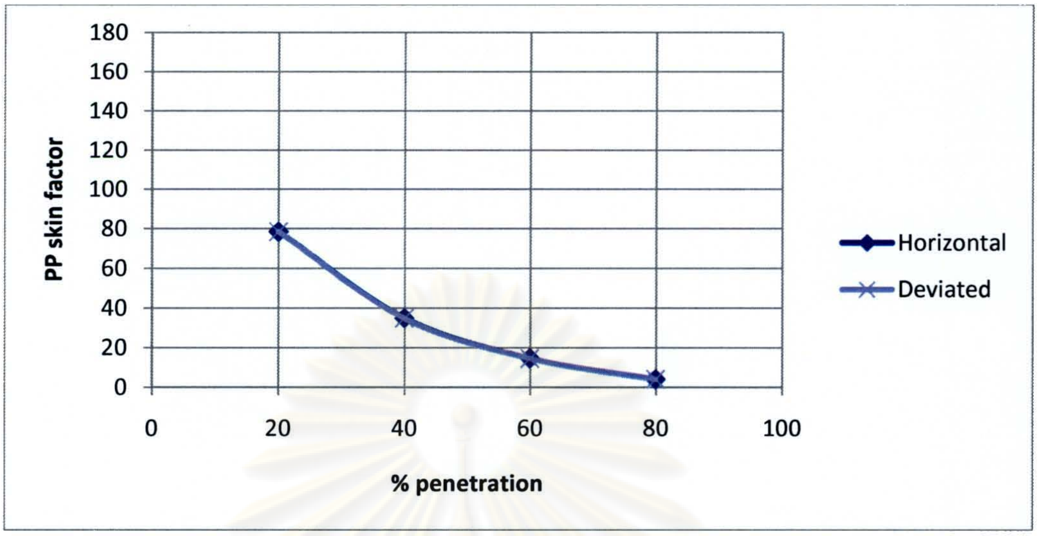

Figure 4.73: Comparison of partial penetration skin factor between for horizontal and the highly deviated wells for L_x = 5,000 ft and reservoir thickness of 100 ft.

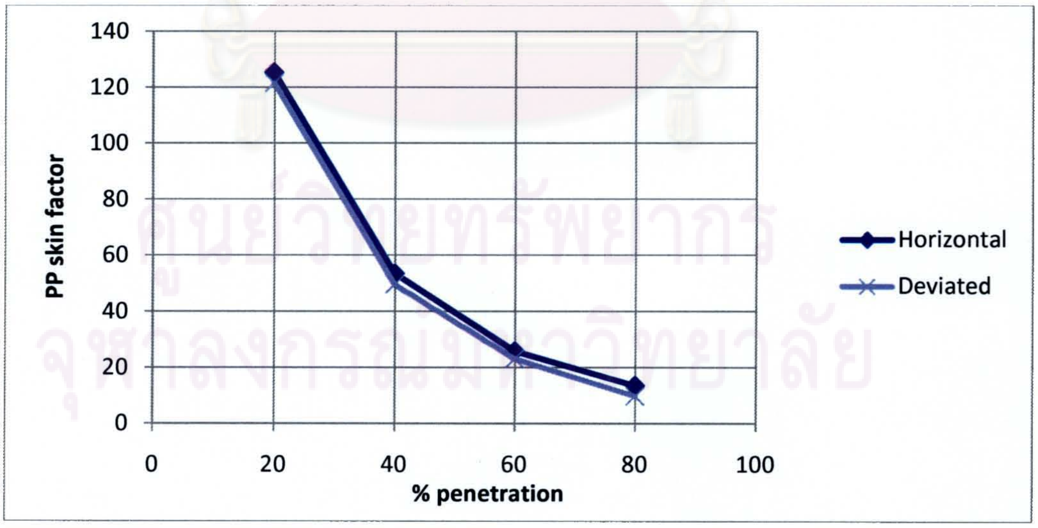

Figure 4.74: Comparison of partial penetration skin factor between for horizontal and the highly deviated wells for L_x = 1,000 ft and reservoir thickness of 250 ft.

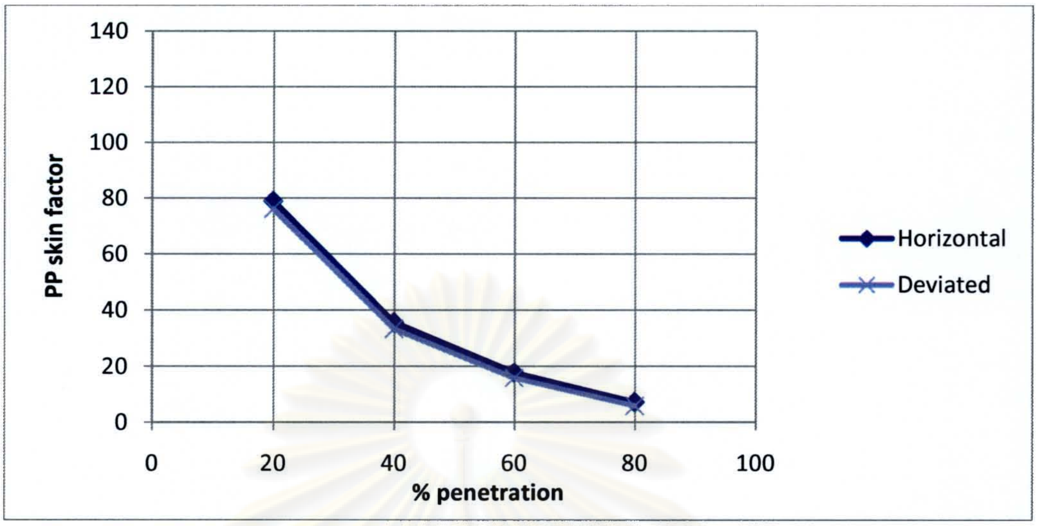

Figure 4.75: Comparison of partial penetration skin factor between for horizontal and the highly deviated wells for L_x *= 2,000 ft and reservoir thickness of 250 ft.*

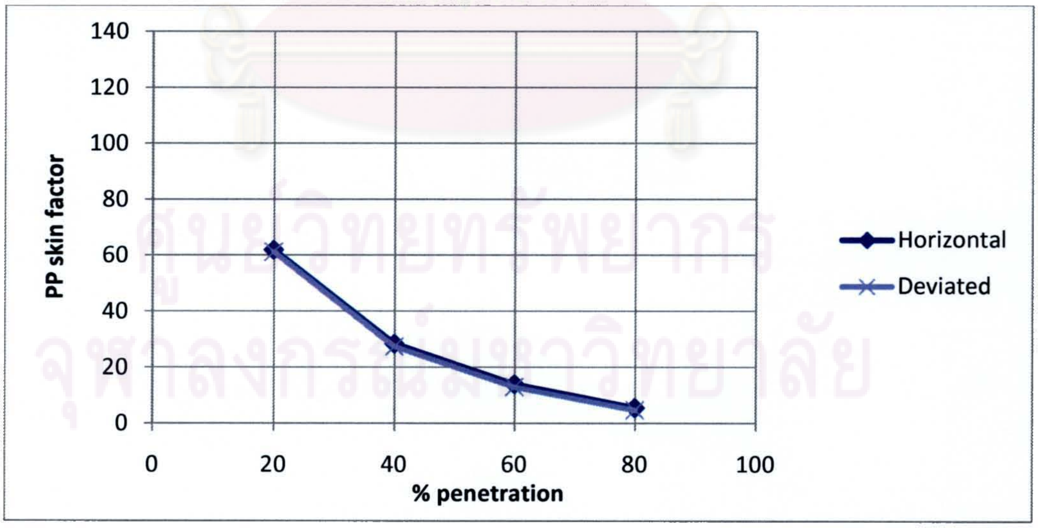

Figure 4.76: Comparison of partial penetration skin factor between for horizontal and the highly deviated wells for L_x *= 3,000 ft and reservoir thickness of 250 ft.*

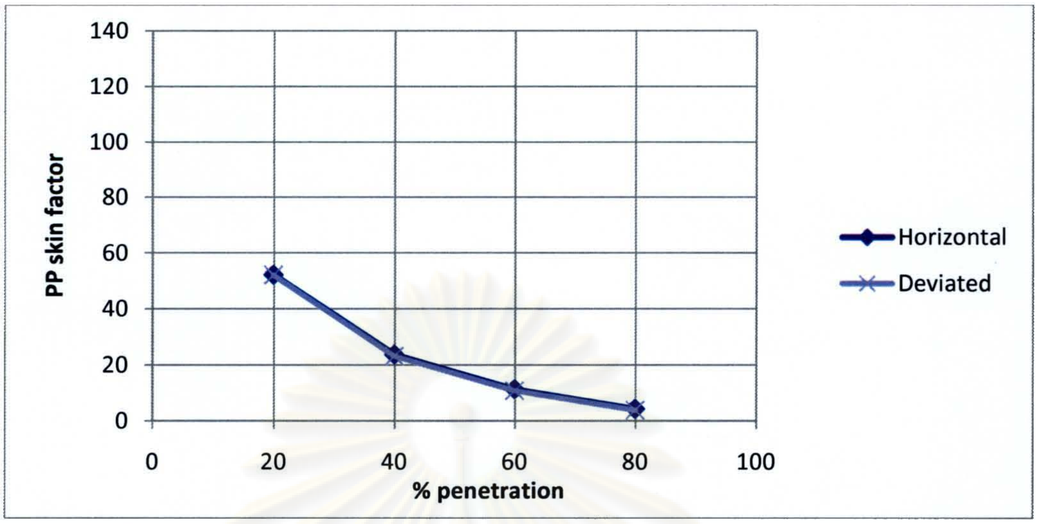

Figure 4.77: Comparison of partial penetration skin factor between for horizontal and the highly deviated wells for L_x = 4,000 ft and reservoir thickness of 250 ft.

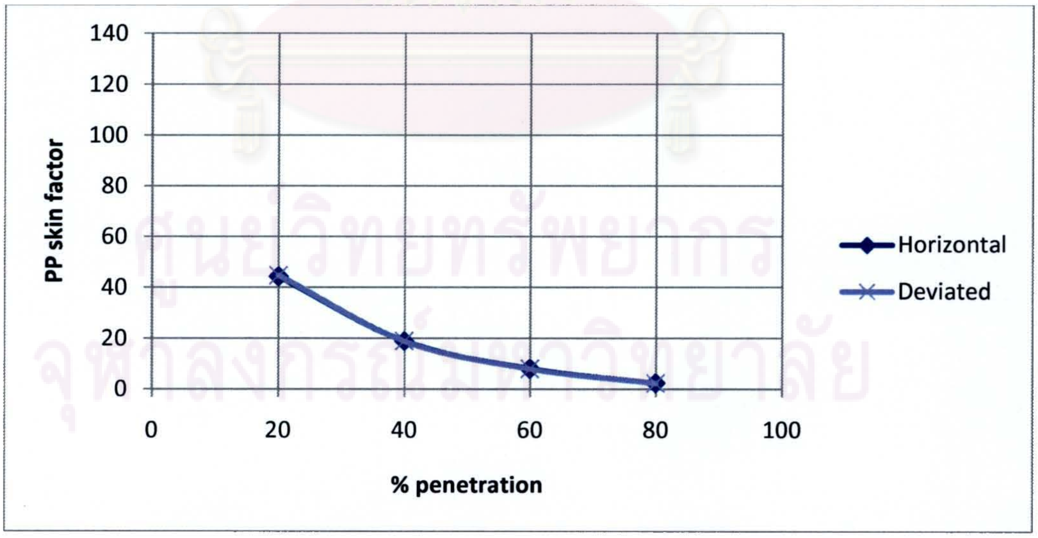

Figure 4.78: Comparison of partial penetration skin factor between for horizontal and the highly deviated wells for L_x = 5,000 ft and reservoir thickness of 250 ft.

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Figures 4.64 to 4.78 show that the partial penetration skin factor for the highly deviated well is very much similar to that for the horizontal well with the same L_x. However, there is some degree of different for a thin reservoir as shown in Figures 4.64 to 4.68. For the reservoir thickness of 50 ft, the skin values are similar when the percent of penetration is high. The difference between partial penetration skin factor of deviated well and horizontal well increases as percent of penetration become lower and as L_x become smaller.

The partial penetration skin factor for the horizontal well was recommended to approximate as that for the highly deviated well. Note that, there is a sensitivity in applying for some cases with thin reservoir, i.e. short L_x (low degree of deviation), and low percent of penetration.

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CHAPTER V

CONCLUSIONS AND RECCOMENDATIONS

This thesis studies the effect of the pressure drop around the horizontal wellbore caused by partial penetration in the reservoir and determines skin factor due to partial penetration for both horizontal and deviated wells using reservoir simulation and compare it with values determined by various methods under different well and reservoir conditions. It is often useful to estimate the size of the partial penetration skin factor since it can be subtracted from the apparent skin to determine whether the well is actually damaged. The skins calculated from the study can then be used to evaluate performance of horizontal wells drilled in various ranges of wellbore, reservoir, and fluid conditions.

The partial penetration skin factor can be determined using analytical equations proposed by (1) Joshi *et al.*, (2) Babu & Odeh, (3) Goode & Kuchuk, and (4) PROSPERS software. In order to study the effect of different parameters on skin factor, we vary reservoir thickness, permeability ratio, well length, wellbore diameter, and oil gravity. The results from all cases show that the relationship between partial penetration skin factor increases as the percent penetration decreases because the limited entry of the connection between the wellbore and reservoir and the converged flow create the additional pressure drop.

The results for different reservoir thicknesses illustrate that the thinner the reservoir, the higher the partial penetration skin factor. The results for different anisotropic ratios illustrate that the partial penetration skin factor is the reverse variation to the anisotropic ratio. A decrease in vertical permeability results in an increase in vertical-flow resistance. In order to maintain the production rate, the pressure drop must be higher. The results for wellbore diameter and oil gravity depict a little difference between the cases. In summary, partial penetration skin factor is sensitive to the reservoir thickness and permeability anisotropic ratio but is not sensitive to wellbore diameter and oil gravity.

The hypothetical reservoirs and well models were constructed using reservoir simulator ECLIPSE 100. Numerous simulations investigating different reservoir thicknesses and anisotropic ratios were run in order to study effect of the pressure drop around the horizontal wellbore caused by partial penetration. The results from the simulation study indicate that thin reservoirs have higher skin factors because they have limited flow in the vertical direction.

The results from analytical equations and PROSPER software are then compared with those obtained from reservoir simulation. The coefficient of determination (R^2) of the 45 degree line is used to indicate the accuracy of each method compared to reservoir simulation. The results show that the partial penetration skin factor determined by Goode & Kuchuk analytical equation has the highest R^2 value of 98.59%. Goode & Kuchuk equation available in PROSPER has the lowest R^2 value of 85.07%. We can conclude that the value of partial penetration skin factor obtained from Goode & Kuchuk equation is the most accurate while Goode & Kuchuk equation available in PROSPER is the least accurate when compared with those obtained from reservoir simulation. Furthermore, the results indicate that all analytical equations and PROSPER software have a limitation when anisotropic ratio is very low and the well penetrates a small portion of the reservoir.

For the deviated well, there are some simplified equations that can determine the skin factor due to deviation. However, the degree of deviation which is applicable for these equations must be less than 75 degree. The deviated wells in the range of 0-75 degree were defined as the slightly deviated well. We can determine the partial penetrating skin factor for slightly deviated by (1) matching the pressure histories and (2) determine the total skin factor. We determine deviated skin using analytical equations (Cinco *et al*., Besson, and Roger & Economides) and compare to those obtained from reservoir simulation. The deviated skin factor from the analytical equations are closed to the values obtained in the simulation. The difference between total skin factor and deviated skin factor were determined as the partial penetration skin factor. The results show that method (1) and (2) give the same results. And the partial penetration skin decreases when the degree of deviation increases.

The deviated well with the degree of deviation more than 75 degree, is defined as the highly deviated well. There is no simplified equation for the deviated well in this range. The effect of partial penetration on the highly deviated well was studied using ECLIPSE 100. The result show that the partial penetration skin factor decreases when the degree of deviation increases, similar to what occurs in the slightly deviated well. The results for different reservoir thicknesses are similar to those obtained from the horizontal well model because the well trajectory of a highly deviated well is close to that of a horizontal well. The partial skin factors for horizontal well are a bit higher than those of the deviated well due to less exposure into the reservoir than the horizontal well. We can conclude that the thinner the reservoir, the higher the partial penetration skin factor. The results for different anisotropic ratios show that the partial penetration skin factors of the deviated well are less than those of the horizontal well. For the deviated well, the fluid can flow into the wellbore in horizontal plane even when the vertical permeability is 0. So, in the case with a very low anisotropic ratio, i.e. k_v/k_h= 0.01, with small portion of partially penetrated into the reservoir, the deviated well shows less partial penetration skin factor than the horizontal well and the partial penetration skin factor is the reverse variation to the anisotropic ratio. The comparison of partial penetration skin factor between horizontal and the highly deviated wells show that the partial penetration skin factor for highly deviated well is very much similar to that for the horizontal well with the same length in the horizontal plane. However, there is some degree of difference for a thin reservoir. The difference between partial penetration skin factor of deviated well and horizontal well increases as percent of penetration become lower and as length in the horizontal plane become smaller is the partial penetration skin factor for the horizontal well is recommended to be used for the highly deviated well.

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APPENDIX

ศูนย์วิทยทรัพยากร
จุฬาลงกรณ์มหาวิทยาลัย

ECLIPSE script for the base case of horizontal well model with operating flow rate of 1,000 RB/D.

RUNSPEC Section

```
TITLE
title
START
 1 'JAN' 2000 /
FIELD
 OIL
 WATER
 NSTACK
 100 /
MONITOR
 RSSPEC
 NOINSPEC
DISPDIMS
 1 2 1 /
 DIMENS
 100 51 51 /
SCDPDIMS
```

ศูนย์วิทยทรัพยากร
จุฬาลงกรณ์มหาวิทยาลัย

0 0 0 0 0 /

EQLDIMS

1 100 100 1 20 /

REGDIMS

1 1 0 0 /

TABDIMS

1 1 20 20 1 20 20 1 /

WELLDIMS

2 101 2 2 /

ศูนย์วิทยทรัพยากร
จุฬาลงกรณ์มหาวิทยาลัย

SCAL Section

SWOF

-- Water/Oil Saturation Functions

0.1	0	1	0
0.17222222	0.00015241579	0.70233196	0
0.24444444	0.0024386526	0.47050754	0
0.31666667	0.012345679	0.2962963	0
0.38888889	0.039018442	0.17146776	0
0.46111111	0.095259869	0.087791495	0
0.53333333	0.19753086	0.037037037	0
0.60555556	0.36595031	0.010973937	0
0.67777778	0.62429508	0.0013717421	0
0.75	1	0	0
1	1	0	0

/

PVT Section

-- Water PVT Properties

PVTW

-- Water PVT Properties

2500 1.03361 5.07e-006 0.32457 1*

/

PVDO

-- Dead Oil PVT Properties (No Dissolved Gas)

1000	1.02682	2.46043
1222.22	1.02676	2.4943
1444.44	1.02672	2.52818
1666.67	1.0267	2.56205
1888.89	1.02667	2.59592
2111.11	1.02666	2.6298
2333.33	1.02664	2.66367
2555.56	1.02663	2.69754
2777.78	1.02662	2.73142
3000	1.02661	2.76529

/

DENSITY

-- Fluid Densities at Surface Conditions

53.2709	60.2873	3.1935

/

ศูนย์วิทยทรัพยากร
จุฬาลงกรณ์มหาวิทยาลัย

ECHO

ROCK

-- Rock Properties

2500 3.06041338506951e-006

/

INIT Section

ECHO

EQUIL

-- Equilibration Data Specification

4000 2500 5000 1* 1* 1* 1* 1* 1* 1* 1*

/

ศูนย์วิทยทรัพยากร
จุฬาลงกรณ์มหาวิทยาลัย

SCHEDULE Section

```
ECHO

WELSPECS

'TEST' '1' 1 26 4000 'OIL' 1* 'STD' 'SHUT' 'YES' 1* 'SEG' 3* 'STD' /

/

RPTSCHED

'RESTART=2' /

COMPDAT

'TEST' 1 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /

/

COMPDAT

'TEST' 2 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /

/

COMPDAT

'TEST' 3 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /

/

COMPDAT

'TEST' 4 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /

/


COMPDAT

'TEST' 5 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /
```

ศูนย์วิทยทรัพยากร
จุฬาลงกรณ์มหาวิทยาลัย

```
/
COMPDAT
'TEST' 6 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /
/
COMPDAT
'TEST' 7 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /
/
COMPDAT
'TEST' 8 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /
/
COMPDAT
'TEST' 9 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /
/
COMPDAT
'TEST' 10 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /
/
COMPDAT
'TEST' 11 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /
/
COMPDAT
'TEST' 12 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /
/
```

ศูนย์วิทยทรัพยากร
จุฬาลงกรณ์มหาวิทยาลัย

COMPDAT

'TEST' 13 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /

/

COMPDAT

'TEST' 14 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /

/

COMPDAT

'TEST' 15 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /

/

COMPDAT

'TEST' 16 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /

/

COMPDAT

'TEST' 17 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /

/

COMPDAT

'TEST' 18 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /

/

COMPDAT

'TEST' 19 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /

/

COMPDAT

ศูนย์วิทยทรัพยากร
จุฬาลงกรณ์มหาวิทยาลัย

```
'TEST' 20 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /
/
COMPDAT
'TEST' 21 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /
/
COMPDAT
'TEST' 22 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /
/
COMPDAT
'TEST' 23 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /
/
COMPDAT
'TEST' 24 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /
/
COMPDAT
'TEST' 25 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /
/
COMPDAT
'TEST' 26 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /
/
COMPDAT
'TEST' 27 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /
```

ศูนย์วิทยทรัพยากร
จุฬาลงกรณ์มหาวิทยาลัย

```
/
COMPDAT
'TEST' 28 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /
/
COMPDAT
'TEST' 29 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /
/
COMPDAT
'TEST' 30 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /
/
COMPDAT
'TEST' 31 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /
/
COMPDAT
'TEST' 32 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /
/
COMPDAT
'TEST' 33 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /
/
COMPDAT
'TEST' 34 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /
/
```

ศูนย์วิทยทรัพยากร
จุฬาลงกรณ์มหาวิทยาลัย

```
COMPDAT
'TEST' 35 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /
/
COMPDAT
'TEST' 36 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /
/
COMPDAT
'TEST' 37 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /
/
COMPDAT
'TEST' 38 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /
/
COMPDAT
'TEST' 39 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /
/
COMPDAT
'TEST' 40 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /
/
COMPDAT
'TEST' 41 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /
/
COMPDAT
```

ศูนย์วิทยทรัพยากร
จุฬาลงกรณ์มหาวิทยาลัย

'TEST' 42 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /

/

COMPDAT

'TEST' 43 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /

/

COMPDAT

'TEST' 44 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /

/

COMPDAT

'TEST' 45 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /

/

COMPDAT

'TEST' 46 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /

/

COMPDAT

'TEST' 47 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /

/

COMPDAT

'TEST' 48 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /

/

COMPDAT

'TEST' 49 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /

ศูนย์วิทยทรัพยากร
จุฬาลงกรณ์มหาวิทยาลัย

```
/
COMPDAT
'TEST' 50 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /
/
COMPDAT
'TEST' 51 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /
/
COMPDAT
'TEST' 52 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /
/
COMPDAT
'TEST' 53 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /
/
COMPDAT
'TEST' 54 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /
/
COMPDAT
'TEST' 55 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /
/
COMPDAT
'TEST' 56 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /
/
```

ศูนย์วิทยทรัพยากร
จุฬาลงกรณ์มหาวิทยาลัย

COMPDAT

'TEST' 57 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /

/

COMPDAT

'TEST' 58 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /

/

COMPDAT

'TEST' 59 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /

/

COMPDAT

'TEST' 60 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /

/

COMPDAT

'TEST' 61 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /

/

COMPDAT

'TEST' 62 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /

/

COMPDAT

'TEST' 63 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /

/

COMPDAT

ศูนย์วิทยทรัพยากร
จุฬาลงกรณ์มหาวิทยาลัย

```
'TEST' 64 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /
/
COMPDAT
'TEST' 65 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /
/
COMPDAT
'TEST' 66 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /
/
COMPDAT
'TEST' 67 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /
/
COMPDAT
'TEST' 68 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /
/
COMPDAT
'TEST' 69 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /
/
COMPDAT
'TEST' 70 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /
/
COMPDAT
'TEST' 71 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /
```

ศูนย์วิทยทรัพยากร
จุฬาลงกรณ์มหาวิทยาลัย

```
/
COMPDAT
'TEST' 72 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /
/
COMPDAT
'TEST' 73 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /
/
COMPDAT
'TEST' 74 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /
/
COMPDAT
'TEST' 75 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /
/
COMPDAT
'TEST' 76 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /
/
COMPDAT
'TEST' 77 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /
/
COMPDAT
'TEST' 78 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /
/
```

ศูนย์วิทยทรัพยากร
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COMPDAT

'TEST' 79 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /

/

COMPDAT

'TEST' 80 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /

/

COMPDAT

'TEST' 81 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /

/

COMPDAT

'TEST' 82 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /

/

COMPDAT

'TEST' 83 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /

/

COMPDAT

'TEST' 84 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /

/

COMPDAT

'TEST' 85 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /

/

COMPDAT

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'TEST' 86 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /

/

COMPDAT

'TEST' 87 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /

/

COMPDAT

'TEST' 88 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /

/

COMPDAT

'TEST' 89 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /

/

COMPDAT

'TEST' 90 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /

/

COMPDAT

'TEST' 91 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /

/

COMPDAT

'TEST' 92 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /

/

COMPDAT

'TEST' 93 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /

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```
COMPDAT
'TEST' 94 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /
/
COMPDAT
'TEST' 95 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /
/
COMPDAT
'TEST' 96 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /
/
COMPDAT
'TEST' 97 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /
/
COMPDAT
'TEST' 98 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /
/
COMPDAT
'TEST' 99 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /
/
COMPDAT
'TEST' 100 26 26 26 'OPEN' 2* 0.489583333 3* 'X' 1* /
/
```

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WCONPROD

'TEST' 'OPEN' 'ORAT' 1000 4* 1000 3* /

/

WECON

'TEST' 100 4* 'NONE' 'YES' 1* 'RATE' 1* 'NONE' 2* /

/

SUMMARY Section

FPR

WBHP

/

WOPR

/

ศูนย์วิทยทรัพยากร
จุฬาลงกรณ์มหาวิทยาลัย

VITAE

Thanitha Wongsawat was born on October, 1983 in Bangkok, Thailand. She received his B.Sc. in Petrochemical Technology (International Program) from the Faculty of Science, King Mongkut's Institute of Technology Lardkrabang in 2005. After graduating, she worked for Showa Kosan (Thailand) company for half year and then she resigned her work to study the Master of Petroleum Engineering at the Department of Mining and Petroleum Engineering, Faculty of Engineering, Chulalongkorn University.

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