ANALYSIS OF FORMATION DAMAGE DURING DRILLING OF DEVIATED WELLS

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ABSTRACT

Filtrate losses and filter cake properties of drilling fluids are of concern in the oil industry because they alter near wellbore permeability and can reduce well productivity. Therefore, it is desirable to accurately characterize filtration process during oil well drilling. A mathematical model for analyzing mud filtration in deviated wells was developed in this study. The model determined solid pressure distribution within cake, cake thickness, cumulative volume of filtrate and extent of invasion under different conditions.

Results show assumptions of isotropy in previous studies greatly overestimate the magnitude of the damage. It was also confirmed that mud filtration tend to be higher in deviated than in vertical wells. The model was validated with experimental data.

Key words: Formation damage, Filter cake, Mathematical model, Mud filtration, Deviated well

INTRODUCTION

Filtration is the process by which mud filtrate enters a permeable formation as a result of pressure differential between the mud column in the well bore and the formation pressure. It is the primary cause of formation damage during oil well drilling. Mud filtration occurs under dynamic conditions where mud is circulated over the filter cake, so that the cake is simultaneously eroded and deposited, or under static conditions where the slurry remains static and filter cake continues to grow thicker as filtration continues. However, in both static and dynamic filtration, the volume of invasion depends little on formation properties and strongly on factors such as mud cake permeability and differential pressure. Formation damage is a more serious problem in many deviated wells than horizontal and vertical wells, because of longer contact time with drilling fluids. Considerable resources have been spent in the oil industry to control both filtrate and filter cake properties of drilling fluids with a view to reducing their formation damage effects. Initially, studies were aimed at improving fluid loss additives, but much effort went later into the development of new and better performing drilling fluids. The first study reported in the literature on filter loss was made by Rubel (1932), he showed that formation damage resulting from invasion of drilling fluid is a major cause of low productivity in wells. Larsen (1938), showed the relationship between filtrate volume and filtration time, as a square root of time. A mathematical modeling of the filtration process was presented by Outmans (1963), he described the mechanism of filtration with a theoretical empirical nonlinear diffusion equation which under certain circumstances can be linearized and solved explicitly. Using his equation, he was able to obtain the equilibrium dynamic fluid data. He concluded that some of the quantities governing dynamic filtration mechanism such as static filter loss are adequate for evaluating dynamic fluid loss. Peden, *et al* (1984) showed that under dynamic condition higher annular velocity and shear rate give rise to an increase fluid loss which is also attributed to reduction the fluid viscosity for static filtration. It was concluded that an increase in concentration of the weighting material results in a reduction in fluid loss, an increase in cake thickness and an increase in cake permeability. Liu *et al.* (1993) developed a model for the simulation and prediction of drilling mud invasion and mud cake formation as well as their impact on formation damage. The model can stimulate the invasion of water or oil base drilling fluid into the formation. In single or two phase flow systems, this model's result agrees reasonably with experimental results. Civan (2001) developed model on permeability reduction due to migration of fine particles in porous media and indicated that permeability damage is more likely to be severe near the well bore. Yim (1999) carried out an experimental study on the effect of sediments on cake filtration data for an inclined pipe, it was concluded that the exact average specific cake resistance can be obtained with filtration data, if the exact mass fraction of solids entering into cake is used. Adel and Ahmed (2008) investigated the effect of completion and workover fluids on formation damage, the study showed that low damage was caused by low density fluid and high damage was caused by high density fluids.

FILTER CAKE MODEL DEVELOPMENT

The filtration through a compressible mud cake can be described by combining the law of conservation of mass, equation of state and Darcy's equation to give:

$$q = \frac{KA}{\mu}\left(\frac{\partial P}{\partial x} + \rho g \sin \theta\right) \qquad (1)$$

Substituting (1) for filtration through an elemental filter cake volume ∂v located between x and x+∂x, y+∂y and z+∂z, we have:

$$-\partial\frac{\partial v}{\partial t} = \left[\frac{\partial}{\partial y}\left(\frac{K_y}{\mu}\left(\frac{\partial P}{\partial y} + \rho g \sin\theta\right)\right)\partial y + \frac{\partial}{\partial z}\left(\frac{K_z}{\mu}\frac{\partial P}{\partial z}\right)\partial z\right]\partial v \qquad (2)$$

According to Terzaghi and Peck, the cake compaction, is due to the action of the solid pressure P_s and that the sum of P_s and fluid pressure P, is at all times equal to the total pressure P_t which is the filtration pressure, i.e. Effective stress + Neutral stress = Total stress

or $$P_s + P = P_t \qquad (3)$$

$$P_s = P_t - P \qquad (4)$$

Since it is only P_s that is responsible for all measurable effects of a change in stress and since P_t is always constant, differentiating (2b) and rearranging, we have:

$$\frac{\partial P}{\partial x} = -\frac{\partial P_s}{\partial x} \qquad (5)$$

The compressibility of any medium changes in volume under the influence of an external pressure P_s and given as: $a_c = -\frac{1}{\partial V}\frac{\partial(\partial V)}{\partial P_s}$ (6)

Differentiating P_s with respect to time gives: $-a_c \partial V\frac{\partial P_s}{\partial t} = \frac{\partial(\partial V)}{\partial P_s}$ (7)

Substituting (7) in (2) and applying transverse isotropic formation (i.e. $K_x = K_y = K_D$ and $K_z = K_v$) we have: $a_s \frac{\partial P_s}{\partial t} = \frac{1}{\mu}\left(\frac{\partial}{\partial y}\left(\frac{\partial P_s}{\partial y} + \rho g \sin \theta\right) + \frac{\partial}{\partial z}\left(\frac{\partial P_s}{\partial z}\right)\right)$ (8)

In terms of stress function, the general non-linear diffusivity equation describing the filtration through a compressible medium in the deviated-horizontal-vertical direction around the wellbore is obtained as:

$$\left(\frac{\partial}{\partial y}\left(J\psi^{\alpha}\frac{\partial \psi}{\partial y} + \rho g \sin\theta\right) + \frac{\partial}{\partial z}\left(J\psi^{\alpha}\frac{\partial \psi}{\partial z}\right)\right) = \frac{\mu a_s}{K_{eq}}\left(J\psi^{\alpha}\frac{\partial \psi}{\partial t}\right) \qquad (9)$$

Mud Cake Buildup Equation

The mud cake buildup can be mathematically expressed as:

$$\frac{\partial h}{\partial t} = c_v q \qquad (10)$$

Where c_v = specific filter cake volume is the constant of proportionality

q = filtrate through put and h = thickness of the cake

Applying Terzaghi's stress theory equation (4) and (9) to equation (10), the mud cake buildup equation is given as:

$$\frac{\partial h}{\partial t} = \frac{c_v K_{eq} A}{\mu}\left(\left(J\psi^{\alpha}\frac{\partial \psi}{\partial y} + \rho g \sin\theta\right) + \left(J\psi^{\alpha}\frac{\partial \psi}{\partial z}\right)\right) \qquad (11)$$

This equation represents the moving boundary condition for the diffusivity equation.

Cumulative Filtrate Volume

The cumulative filtrate volume at a given time t, with rate q at the filtrate through put is expressed as: $Q = \int - q\, \partial t$ (12)

Where per unit area, $q = \frac{K_{eq}}{\mu}\left(\left(\frac{\partial P_s}{\partial y} + \rho g \sin\theta\right) + \frac{\partial P_s}{\partial z}\right)$ (13)

Substituting equation (13) into equation (12), the general equation that describes the filtrate volume at a given time is expressed as:

$$Q = \int \frac{-K_{eq}}{\mu}\left(\left(J\psi^{\alpha}\frac{\partial \psi}{\partial y} + \rho g \sin\theta\right) + \left(J\psi^{\alpha}\frac{\partial \psi}{\partial z}\right)\right)\partial t \qquad (14)$$

As drilling of inclined well progresses, the well is exposed to drilling fluids longer than expected. This will result in cake buildup with the larger base near the vertical section of the well. The boundary conditions for the solution of the equations governing the system of filtration process in an incline well include: inner boundary, outer boundary, and moving boundary conditions.

SOLUTION DEVELOPMENT

The mathematical solution obtained is polynomial approximation. The derived equation for pure radial flow of filtrate through a highly compressible cake in the wells system is non-linear third order equation.

Inner boundary condition

When the filtration process begins, some cake is deposited at the wall of the bore. In this case we have the fluid pressure of zero constant i.e. $P_f = 0$ and $P_T = P_s$

We therefore have the stress condition becoming

$$\psi\,(y_o,t) = \psi(y_o) = \psi = f(y)t \geq \qquad (15)$$

Where ψ_0 is defined by: $\psi = \dfrac{k\varnothing_o P_1^{-(k+\beta)}}{E(k+\beta)}$ (16)

Outer boundary condition

As the drilling of the deviated well goes on, the well is exposed to drilling fluids however before the filtration commences, no cake is formed. This implies that there is no solid pressure; we therefore left with the fluid pressure i.e. $P_T = P$ as $P_s = 0$ this means the function become zero i.e. $\psi_o = 0$. We have: $\psi\,(h,t) = \psi\,(o,t) = 0\ t \geq 0$ (17)

Applying the boundary conditions to solving equation (9), assuming α=2 for a compressible fluid and comparing with 2-D heat equation we have:

$$\frac{\partial \psi}{\partial y}(y,t)=\frac{2}{h}(\psi_o)e^{-\frac{\psi\lambda^2}{k_c}t} \qquad (18)$$

and $\frac{\partial \psi}{\partial z}(z,t)=\frac{8}{h}(\psi_o)e^{-\frac{\psi\lambda^2}{k_c}t}$ (19)

$$K_c = \frac{JK_{eq}}{\mu} \qquad (20)$$

Substituting (17) in equations (11) and (14), we have

$$h^2 = \frac{2C_v K_{eq} A\rho g \sin\theta t}{\mu} - \frac{20 C_v K_{eq} AJk_c \psi(\psi_o)e^{-\frac{\psi\lambda^2}{k_c}t}}{\lambda^2 \mu} \qquad (21)$$

or $h^2 = B_1 t - B_2 e^{-B_3 t}$ (22)

$$h = \left(B_1 t - B_2 e^{-B_3 t}\right)^{1/2} \qquad (23)$$

From equation (23) it can be deduced that cake thickness increases with the square-root of time. Fig.1 shows that the cake increases with time until it a maximum it begins to reduce. The cake thickness depends on the mud property of the drilling fluid (i.e. α=2 and α=3) and the reservoir permeability. Fig.2 shows the plot of cake thickness against solid pressure at constant of non-linearity.

$$Q = -\frac{K_{eq}}{\mu}\left(\rho g \sin\theta t - \frac{8J\psi k_c(\psi_o)e^{-\frac{\psi\lambda^2}{k_c}t}}{\lambda^2 h}\right) \qquad (19)$$

$$Q = \frac{B_2}{8h}e^{-B_3 t} - \frac{B_1}{2C_v A}t \qquad (20)$$

$$Q = B_4 e^{-B_3 t} - B_5 t \qquad (21)$$

Equation (21) reveals that specific cake volume and as well as other mud properties can be controlled in order to reduce volume of filtrate.

DISCUSSION

The solution stress function is given by the equation (17) which shows that the stress function depends on the distance from the wall cake interface, the cake thickness and an arbitrary constant J. The J constant depends on the specific cake volume, solid pressure function, mud cake interface and the degree of non-linearity. Figure 1 shows that cake thickness increases with time until a maximum before it begins to reduce. Figure 2 shows the plot of cake thickness against solid pressure at constant of non-linearity. Figure 3 shows the plot of cumulative filtration against time. The linear relationship implies that the cumulative filtrate volume increases linearly with time at different values of cake compressibility. Figure 4 shows the plot of filtrate volume against the angle of deviation. It shows that filtrate volume increases with an increase in angle of deviation at different values of cake compressibility. Figure 5 shows the plot of cake thickness against angle of deviation; cake thickness increases with an angle of deviation at different values of cake compressibility. Fig. 6 shows the plot of solid pressure against cake distance from wall. The filtrate rate and filter cake thickness agreed well with experimental data. Fig. 7 is plot of depth of filtrate and solids invasion versus time for an inclined wells. It also reveals initial spurt loss to the formation and rate of the establishment of a sealing filter cake.

CONCLUSION

An approximate analytical solution using polynomial quadratic profile was applied to solve the filtration equation for a compressible filter cake. The solution shows that, reduction of solid pressure plays a key role in minimizing formation damage (Figures 5 and 6). The behavior of the solid pressure within the cake thickness medium, filtrate volume and radius of invasion are quite sensitive to the degree of non-linearity. Mud viscosity, specific cake volume as well as other mud properties can be controlled in order to reduce the filtrate volume and radius of invasion. This can be achieved with the use of mud additives. Increase viscosity gives rise to reduce volume of filtrate. The effect of filtration on the angle of deviation was determined. This should help in planning and allocation of drilling time in order to reduce formation damage.

NOMENCLATURE

Quantity	Symbol	Unit
1. Flow	q	ft/sec
2. Viscosity	μ	cp
3. Permeability in the deviated direction	K_D	ft^2
4. Permeability in the vertical direction	K_V	ft^2
5. Fluid pressure in the filter cake	P_f	psi
6. Solid pressure in the filter cake	P_s	psi
7. Cumulative filtrate volume per unit area	Q	ft
8. Time	t	sec
9. Length of deviated section	L	ft
10. Specific filter cake volume	C_v	-
11. Cake thickness	h	ft
12. Cake compressibility	a_c	psi^{-1}
13. Specific cake resistance	a_r	ft/ib
14. Mud density	ρ_s	ppg
15. Porosity	$\varnothing$	%
16. Stress function	ψ	

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Figure 1: Cake Thickness versus Time

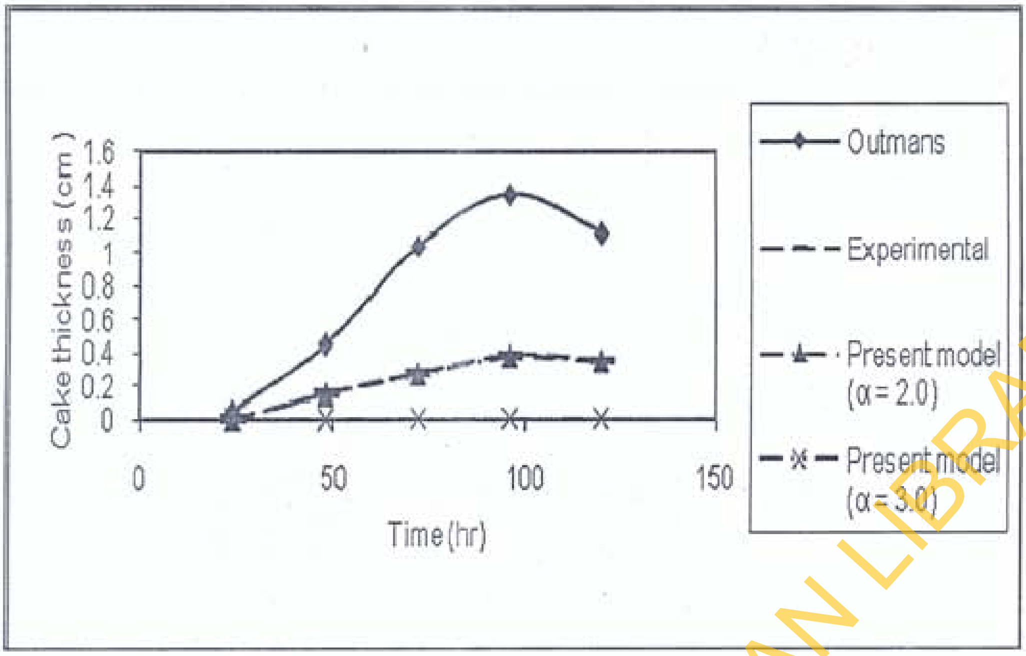

Figure 2: Cake Thickness as a function of Mud Pressure

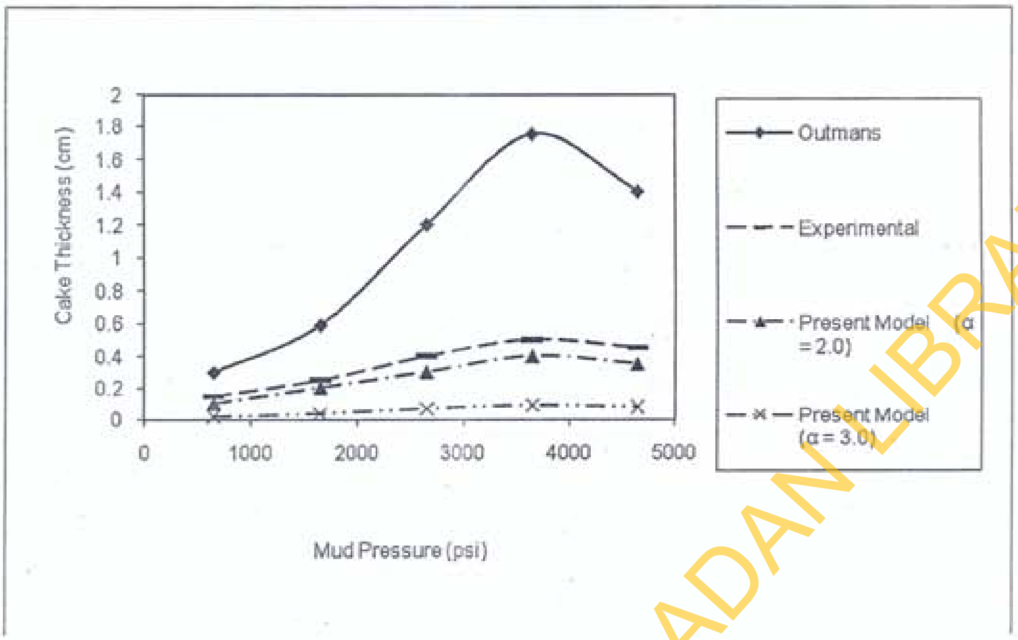

Figure 3: Filtrate Volume against Time in Deviated Well

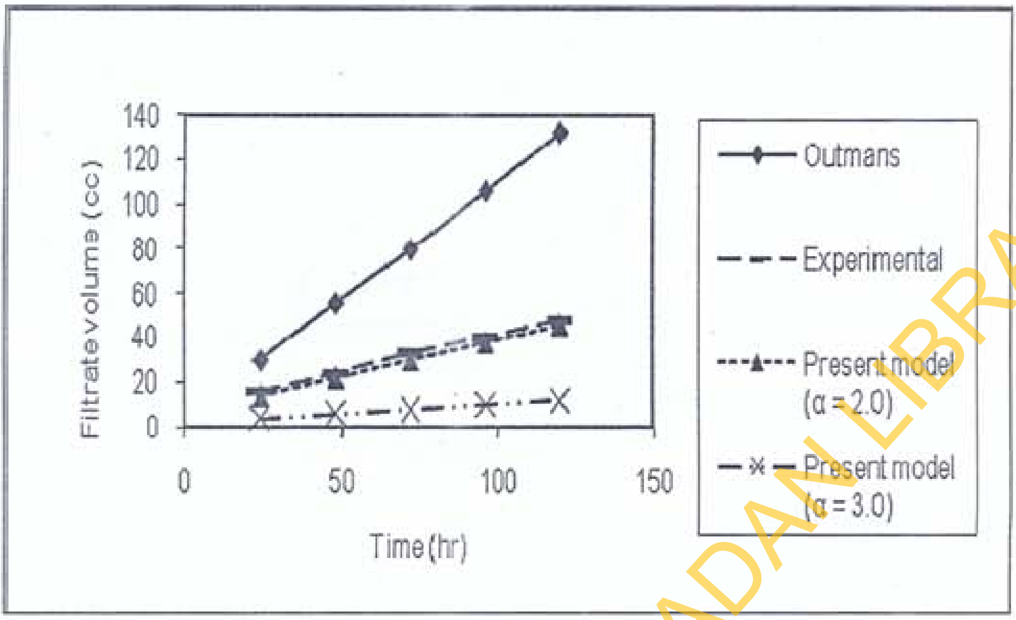

Figure 4: Filtrate Volume versus Deviation Angle

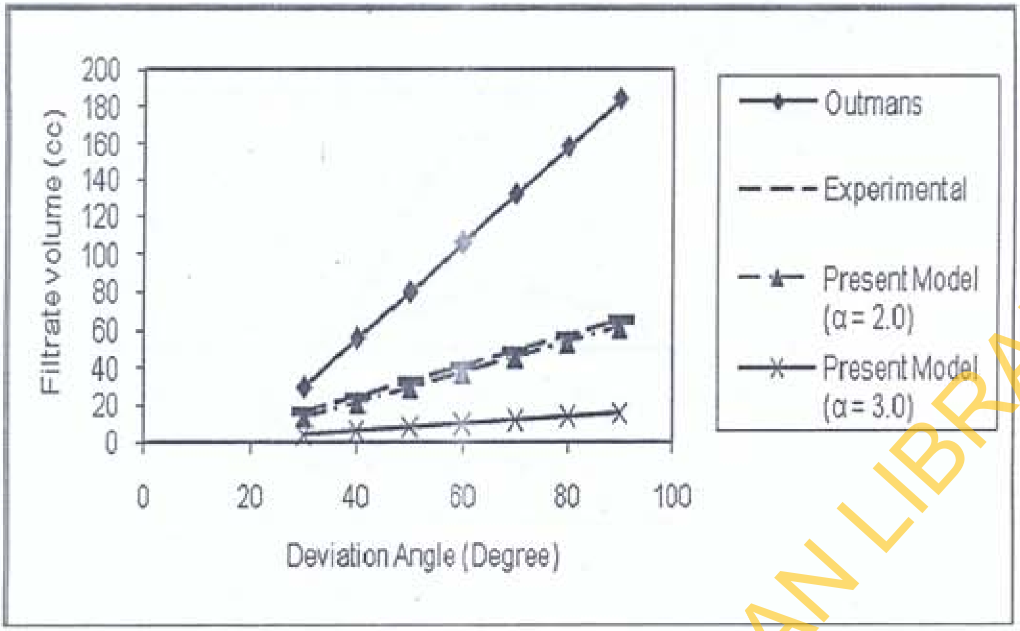

Figure 5: Cake Thickness versus Deviation Angle

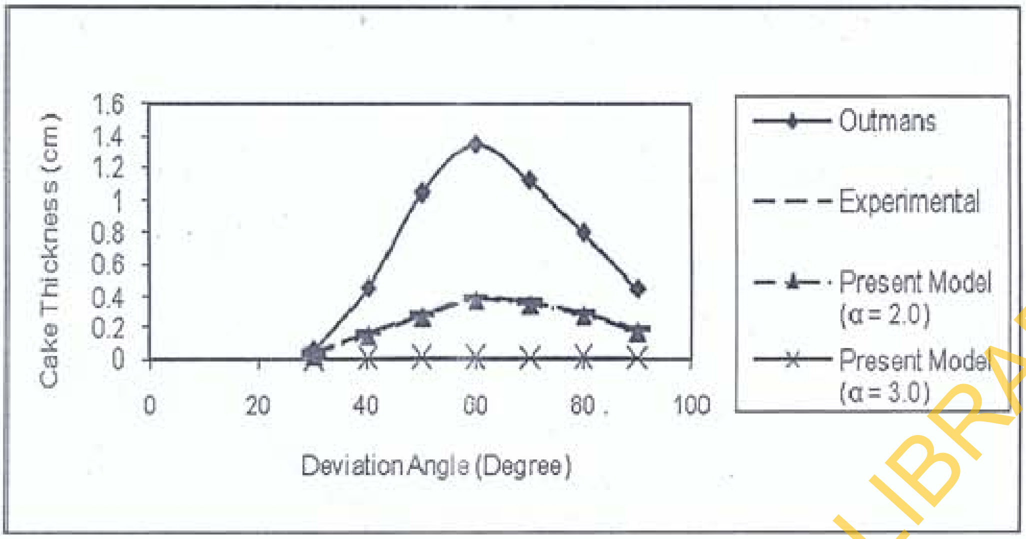

Figure 6: Solid pressure versus Cake Distance from Wall

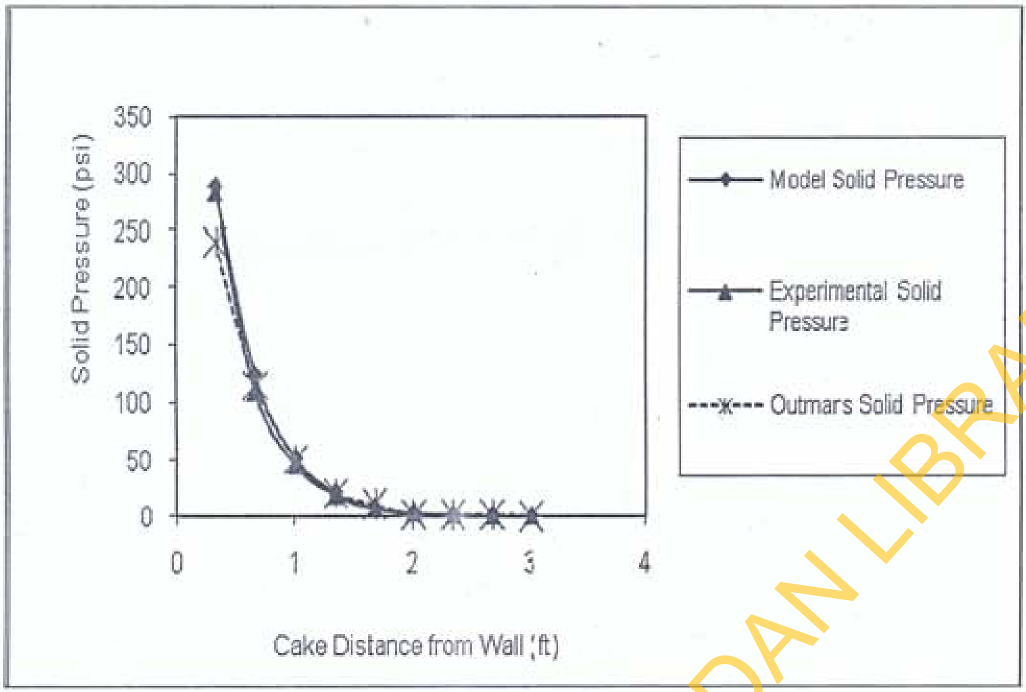

Figure 7: Radius of Invasion versus Time for Deviated Well