

Numerical analysis of the effects of downhole dynamic conditions on formation testing while drilling

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Abstract: Formation testing while drilling is an innovative technique that is replacing conventional pressure testing in which the fluid sampling is conducted in a relatively short time following the drilling. At this time, mud invasion has just started, mudcake has not formed entirely and the formation pressure is not stable. Therefore, it is important to study the influence of the downhole dynamic environment on pressure testing and fluid sampling. This paper applies an oil-water two phase finite element model to study the influence of mudcake quality and mud filtrate invasion on supercharge pressure, pretest and sampling in the reservoirs of different permeability. However, the study is only for the cases with water based mud in the wellbore. The results illustrate that the mudcake quality has a significant influence on the supercharge pressure and fluid sampling, while the level of mud filtrate invasion has a strong impact on pressure testing and sampling. In addition, in-situ formation pressure testing is more difficult in low permeability reservoirs as the mud filtrate invasion is deeper and therefore degrades the quality of fluid sampling. Finally, a field example from an oil field on the Alaskan North Slope is presented to validate the numerical studies of the effects of downhole dynamic conditions on formation testing while drilling.

Key words: Formation testing while drilling, formation supercharge, pressure testing, fluid sampling, finite element method, mudcake, filtrate invasion

1 Introduction

Formation testing while drilling (FTWD), based on drill stem testing (DST) and wireline formation testing (WFT), is an innovation of logging while drilling (LWD). FTWD can not only carry out the function of WFT, such as fluid sampling, pressure and temperature testing, but also can be used for detecting annular pressure and original formation pressure in real time to optimize mud formulation and improve drilling safety. FTWD is suitable for the formation testing of extended reach wells and horizontal wells and hence can reduce the drilling time and cost over WFT (Hou et al, 2005; Lee et al, 2004; Finneran et al, 2005; Pop et al, 2005; Proett et al, 2003; 2004; 2010; 2011; Seifert et al, 2005; Fey et al, 2011; Masoud et al, 2009; Di et al, 2012a; 2012b; 2012c). So far only major international oil service companies have developed their own FTWD tools, such as StethoScope developed by Schlumberger, TesTrak developed by Baker Hughes and Geo-Tap developed by Halliburton. In China, few national companies have been developing the technology

during the National 11th Five-Year Plan and the subsequent National 12th Five-Year Plan. The representational tools are SDC-1 developed by Daqing Drilling Engineering Technology Research Institute and CPWD developed by CNPC Drilling Research Institute (Ren and Ma, 2005; Su and Dou, 2005; Yang and Tian, 2005; Zhang et al, 2006; Li et al, 2008; Wang et al, 2009; Liu et al, 2010; Zhao et al, 2011).

FTWD starts fluid sampling and pressure testing after the drill bit breaks the formation for a short time. The mud invasion has just started but the mudcake has not been formed entirely and the formation pressure is not stable during the procedure. The complicated downhole environment is quite different from that of WFT. Therefore, it is important to consider the influence of the downhole dynamic environment on the pressure testing and sampling. Lee et al (1998) and Sarkar et al (1998) analyzed the influence of mudcake quality, depth of mud filtrate invasion and formation anisotropy on fluid sampling of WFT using the finite element method. However, the effects of mudcake parameters and filtrate invasion on formation supercharge have not been considered. Usually, the mud hydrostatic pressure is set higher than the original formation pressure to ensure drilling safety. Consequently a certain amount of filtrate invasion occurs

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and this in turn leads to a higher formation pressure near the wellbore than the original formation pressure, especially in low permeability formations. This so called supercharge pressure is shown to be a product of the apparent overbalance pressure between the invasion zone and the original formation. On the other hand, the mudcake can also isolate the wellbore from the original formation and prevent the mud filtrate invasion. Therefore, the mudcake permeability has a direct influence on the formation pressure near the wellbore.

A simple equation was formulated for estimating the supercharge pressure, assuming that a steady condition is reached at the time when the FTWD measurements are made (Proett et al, 2011). In the steady state, single-phase flow of filtrate through the mudcake is expressed by Darcy's law as follows

$$q_{mc} = \frac{2\pi k_{mc} h (p_w - p_s)}{\mu \ln \frac{r_s}{r_w}} \quad (1)$$

where $r_s = r_w + l_{mc}$; q_{mc} is the filtrate flow rate through the mudcake, mL/s; k_{mc} is the mudcake permeability, mD; μ is the filtrate viscosity, mPa·s; h is the formation thickness, m; p_w is the liquid column hydrostatic pressure, psi; p_s is the pressure at the mudcake/formation interface, psi; r_w is the wellbore radius, cm; l_{mc} is the mudcake thickness, cm.

Similarly, the steady state flow invading through the formation is expressed as

$$q_f = \frac{2\pi k_f h (p_s - p_f)}{\mu \ln \frac{r_f}{r_s}} \quad (2)$$

where r_f is the radial distance of supercharging, cm; q_f is the filtrate flow rate through the formation, mL/s; p_f is the formation pressure, psi; k_f is the formation permeability, mD. Under steady conditions these two flow rates are equal. Hence,

$$q_{mc} = q_f \quad \text{or} \quad p_f = p_s - \Delta p_{sc} \quad (3)$$

where Δp_{sc} is the supercharge pressure and is defined as

$$\Delta p_{sc} = (p_w - p_s) \frac{k_{mc}}{k_f} \left[\frac{\ln \frac{r_f}{r_w + l_{mc}}}{\ln \frac{r_s + l_{mc}}{r_w}} \right] \quad (4)$$

The above equation indicates that the supercharge pressure is related to the apparent overbalance pressure, the mudcake-to-formation permeability ratio, and the invasion factor.

As the formation testing procedure involves interactions of the downhole tool probe, borehole and formation fluids and solid rocks, as well as mudcake, it possess a typical fluid flow problem in a domain of complex geometry. Finite element methods (FEM) have shown the ability to quantitatively analyze the relationship between the formation pressure and parameters in such a complicated situation. In order to study the effect of the downhole dynamic environment on the pressure testing and fluid sampling, we developed a FEM simulator to study the effects of mudcakes, invasion depth, formation permeability and differential fluid pressure on the pressure testing and fluid sampling.

2 Mathematical model

The process of formation testing while drilling is actually a process of seepage. The water saturation near the wellbore is different from the water saturation of the original formation, and there inevitably exists an oil-water phase near the probe in the process of pumping fluid. Therefore, the mathematical treatment of formation testing is to solve the problem of oil-water two phase flow in the porous medium. According to the principle of the mechanics of fluid flow in porous media, the fundamental derivative equations of oil-water two phase flow in the formation can be derived as follows (Zhou et al, 2003; 2007; Gu et al, 2005a; 2005b; 2007; Yi et al, 1997):

$$\begin{cases} \nabla \cdot \left[\left(\frac{k \cdot K_{ro}(S_w)}{\mu_o} + \frac{k \cdot K_{rw}(S_w)}{\mu_w} \right) \nabla P_o \right] - \nabla \cdot \left[\frac{k \cdot K_{rw}(S_w)}{\mu_w} \nabla P_c(S_w) \right] = \varphi C_{fw}(S_w) \frac{\partial P_o}{\partial t} \\ \nabla \cdot \left[\frac{k \cdot K_{ro}(S_w)}{\mu_o} (\nabla P_o) \right] = \varphi \frac{\partial S_o}{\partial t} + \varphi S_o C_{fo} \frac{\partial P_o}{\partial t} \\ P_o|_{t=0} = P|_{l \rightarrow \infty} = P_{oi} \\ -k \left(\left(\frac{K_{ro}(S_w)}{\mu_o} + \frac{K_{rw}(S_w)}{\mu_w} \right) \nabla P_o - \frac{K_{rw}(S_w)}{\mu_w} \nabla P_c(S_w) \right) \cdot \pi r_s^2 |_{\text{probe}} = q \end{cases} \quad (5)$$

where k is the absolute permeability of the media, mD; K_{rw} and K_{ro} are the relative permeability to water and oil, respectively; μ_w and μ_o are the water and oil viscosity respectively, mPa·s; P_o and P_w are the oil and water pressures respectively, psi; P_c is the capillary force, psi; S_w is the water saturation; S_o is the oil phase saturation; φ is the formation porosity; C_{fw} is the compression coefficient of the water

phase; C_{fo} is the compression coefficient of the oil phase; q is the flow rate that probe sucks fluid, mL/s; r_s is the radius of probe, cm.

We can obtain relative permeability curves from the data of the numerical reservoir simulation. The relative permeability equations (Eqs. (6)-(8)) were applied in the model.

Water phase:

$$K_{rw}(S_w) = \begin{cases} 0.0 & S_w < 0.21 \\ 1.4437S_w^2 - 0.4758S_w + 0.00434 & 0.81 < S_w < 0.21 \\ K_{rmax} & S_w > 0.81 \end{cases} \tag{6}$$

Oil phase:

$$K_{ro}(S_w) = \begin{cases} 0.788 & S_w < 0.21 \\ 1.5935S_w^2 - 2.9291S_w + 1.3318 & 0.81 < S_w < 0.21 \\ 0 & S_w > 0.81 \end{cases} \tag{7}$$

Capillary pressure equation:

$$P_c(S_w) = 55080.4(1 - S_w)^{1.5} \tag{8}$$

The pressure equation in the mathematical model is an elliptic equation (Eq. (9)), which can be solved by the Garlerkin method,

$$\begin{aligned} & \iiint_{\Omega_e} \left(\frac{k \cdot K_{rw}}{\mu_w} + \frac{k \cdot K_{ro}}{\mu_o} \right) \cdot \nabla P_o \cdot \nabla N_{pi} \cdot d\Omega + \iiint_{\Omega_e} \Phi \cdot C_f \frac{\partial P_o}{\partial t} \cdot N_{pi} \cdot d\Omega_e \\ & = \oint_{\Gamma_e} - \frac{q}{\pi r_s^2} \cdot N_{pi} \cdot \vec{n} \cdot d\Gamma_e + \iiint_{\Omega_e} \frac{k \cdot K_{rw}}{\mu_w} \cdot \nabla P_c \cdot \nabla N_{pi} \cdot d\Omega_e \end{aligned} \tag{9}$$

where $i = 1, 2, 3, \dots, n$; Ω_e is unit area, \vec{n} is the boundary normal; N_{pi} is the shape function of pressure equation.

For the saturation equation (Eq. (10)), the stiffness matrix in the finite element model established with the Garlerkin method is an ill-conditioned matrix, and the solved equations are pathological equations. Therefore, the least squares method is applied to establish the saturation equation of the finite element model, the equivalent integral weak form of the saturation field equations can be derived as

$$\begin{aligned} & \iiint_{\Omega} \left[\left(\phi + \phi C_{fo} \frac{\partial P_o}{\partial t} \cdot dt \right) \cdot \mathbf{S}_{wi}^{t+1} \right] \cdot \left[\left(\phi + \phi C_{fo} \frac{\partial P_o}{\partial t} \cdot dt \right) \cdot (\mathbf{N}_{sw}^{t+1})^T \right] \cdot d\Omega \\ & = \iiint_{\Omega} \left[\phi S_w^t + \phi C_{fo} \frac{\partial P_o}{\partial t} \cdot dt - \nabla \left(\frac{k K_{ro}}{\mu_o} \nabla P_o \right) \cdot dt \right] \cdot \left[\left(\phi + \phi C_{fo} \frac{\partial P_o}{\partial t} \cdot dt \right) \cdot (\mathbf{N}_{sw}^{t+1})^T \right] \cdot d\Omega \end{aligned} \tag{10}$$

where $i=1, 2, 3, \dots, n$; N_{sw} is the shape function of the saturation equation.

To check the validity of our finite element model, we first computed an example of 3D spherical flow in an isotropic formation, as an analytical solution for this case can be obtained too. A comparison of our numerical results with the analytical solution for the pressure profile at the probe is illustrated in Fig. 1, given the initial formation pressure of 5,000 psi, the formation permeability of 0.1 mD, the flow rate of the probe of 1 mL/s, the diameter of the probe of 1.27 cm, and the formation permeability anisotropy in terms of k_z/k_h of 1. It can be seen that there is almost no difference between the numerical and analytical solutions. The relative errors are less than 0.1%. We thus believe that the finite element model is reliable and accurate enough. The tiny difference between the solutions could be caused by the geometrical simplification in the calculation of the analytical solution.

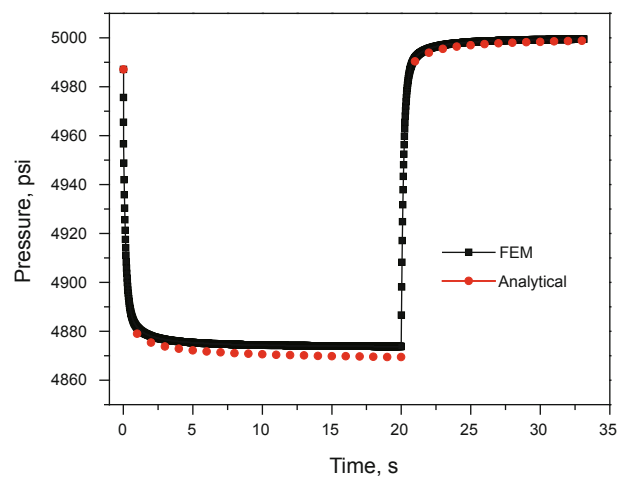


Fig. 1 A comparison of the analytical solution and the finite element calculation (single phase flow)

3 Modeling of changed formation pressure during mud invasion

According to the field cases of downhole mud filtrate invasion and formation supercharging, we established a two-dimensional axisymmetric model in the simulation software, as is shown in Fig. 2. In this model, the wellbore radius is 0.1 m, the model is 10 m in radius and 5 m in thickness. We set up the wellbore, mudcake, mud filtrate and the formation in the model, and assigned the parameters to the different zones respectively according to the real conditions in the field (Table 1).

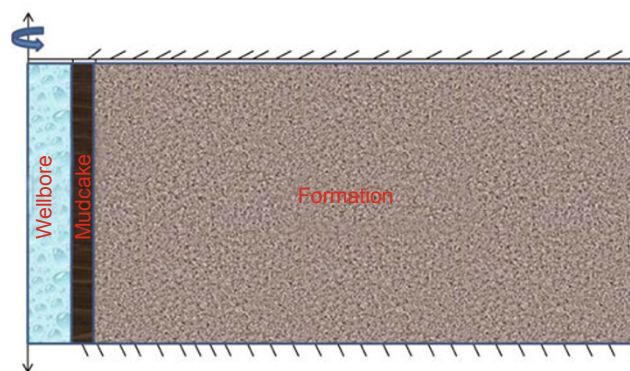


Fig. 2 Two-dimensional axisymmetric geometry for modeling downhole dynamic conditions

Table 1 The parameters for modeling downhole dynamic conditions

	Porosity	Permeability mD	Fluid density kg/m ³	Fluid viscosity mPa·s	Compressibility psi ⁻¹	Pressure psi	Thickness cm
Formation	0.3	1.0	800	1.0	3×10^{-6}	5000	–
Mudcake	0.15	10^{-2} - 10^{-5}	–	1.0	0.1	–	0.5-2.0
Mud filtrate	–	–	1000	0.5	–	5500	–

3.1 Effect of mudcake permeability on supercharge pressure

We first investigated the effect of mudcake permeability on formation supercharge near the wellbore. Initially, assuming that the formation exposed to drilling fluids is completely sealed by the mudcake we started with these parameters: the mudcake thickness is 0.5 cm, the formation permeability is 1 mD, the wellbore pressure is 5,500 psi, both the formation pressure and boundary pressure are 5,000 psi, and other parameters are listed in Table 1. We then increased the mudcake permeability to calculate the formation supercharge step by step. Fig. 3 demonstrates these results from our FEM simulations. From this figure it can be seen that the formation supercharge pressure becomes higher when the mudcake permeability increases. The sandface pressure just behind the mudcake exceeds the formation pressure by 308 psi when the mudcake permeability is 0.01 mD. As the radial distance from the wellbore increases, the supercharging becomes weaker. At the distance of 5 m away from the wellbore, the wellbore pressure has little effect on the formation pressure even though the mudcake quality becomes very poor. As also shown in Fig. 3, as long as the mudcake permeability is less than 10^{-5} mD, the formation supercharge near the wellbore can be ignored. This is because the mudcake deposited on the wellbore face breaks the pressure connection between the wellbore and the formation and the drilling fluid does not flow into the formation, thus the wellbore hydrostatic pressure has little effect on the formation pressure around the wellbore.

FTWD is operated in a short time just after the drill bit breaks the formation. At this moment, some filtrate immediately invades the formation near the wellbore, but the mudcake has not formed entirely and hence the mudcake quality is poor. In such cases, wellbore supercharge may

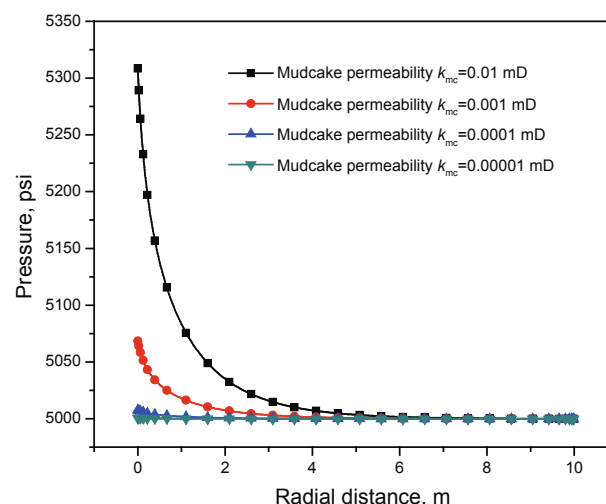


Fig. 3 The effect of mudcake permeability on supercharge pressure

occur near the wellbore and cause problems for FTWD. In field applications, the drilling and logging engineers have to do pressure testing at appropriate locations where the mudcake quality is good and the formation pressure is stable.

3.2 Effect of mudcake thickness on supercharge pressure

We subsequently investigated the influence of mudcake thickness on the formation supercharge pressure given that the formation and the mudcake have permeability of 1 and 10^{-3} mD, respectively. The other parameters of the model are listed in Table 1. These simulation results are shown in Fig. 4. It can be seen that the formation pressure is not affected by the mudcake thickness at the radial distance

of 5 m away from the wellbore. However, the pressure at the borehole wall exceeds the formation pressure by 69 psi when the mudcake thickness is 0.5 cm. On the other hand, when the cake thickness is over 2.0 cm, the supercharging is reduced substantially and can be ignored. This is because that the thicker mudcake formed on the wellbore face better isolates the drilling fluid in the wellbore from the formation, and hence the wellbore hydrostatic pressure has little effect on the formation pressure. Therefore, the location where the mudcake is sufficiently thick (in the case, over 2 cm) should be considered as a candidate formation to be tested.

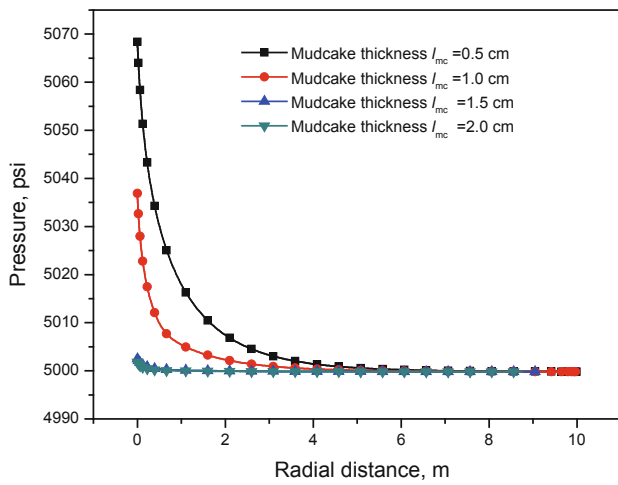


Fig. 4 The effect of mudcake thickness on supercharge pressure

3.3 Effect of formation permeability on supercharge pressure

To investigate the effect of formation permeability on formation supercharge, we analyzed the changes of formation pressure at different formation permeability when the mudcake thickness and permeability were set at 1 cm and 10^{-3} mD. Fig. 5 shows that when the formation permeability is 0.1 mD, the formation pressure near the wellbore exceeds the original formation pressure by 225 psi. With an increase in the formation permeability, the supercharge pressure near the

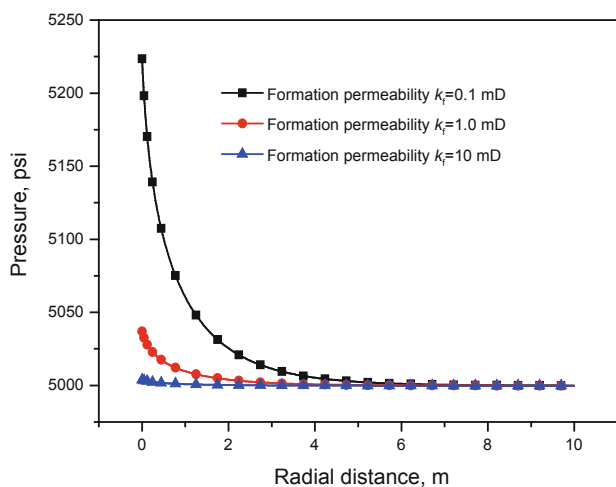


Fig. 5 The effect of formation permeability on supercharge pressure

wellbore becomes lower. When the formation permeability increases to 10 mD, the supercharge pressure decreases substantially and can be ignored. According to the simulation results, the location for pressure testing should be selected where the formation of a permeability over 10 mD.

3.4 Effect of mudcake permeability on fluid sampling

Finally, we analyzed the influence of mudcake permeability on fluid sampling. The simulation parameters are as follows: The cake thickness is 1 cm and the pump rate used is 15 mL/s, the initial saturation of 100% filtrate at the wellbore is followed by a transitional zone of 15 cm to the non-invaded zone. The simulation results are shown in Fig. 6. It can be seen that the sampling quality will substantially degrade when the mudcake permeability is higher than 0.01 mD due to continuous invasion of fresh mud filtrate. Therefore, the mudcake permeability should be considered in fluid sampling in field applications.

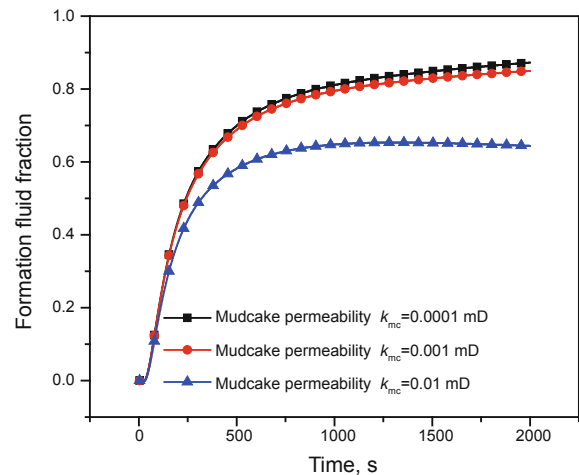


Fig. 6 The effect of mudcake permeability on fluid sampling

4 Effect of mud filtrate invasion on pressure testing and fluid sampling

When the FTWD operation starts, some mud filtrate has invaded into the formation to differing extents. To quantify the effect of filtrate invasion on pressure testing and fluid sampling, we developed a geometrical model (Fig. 7) and the model parameters are listed in Table 2.

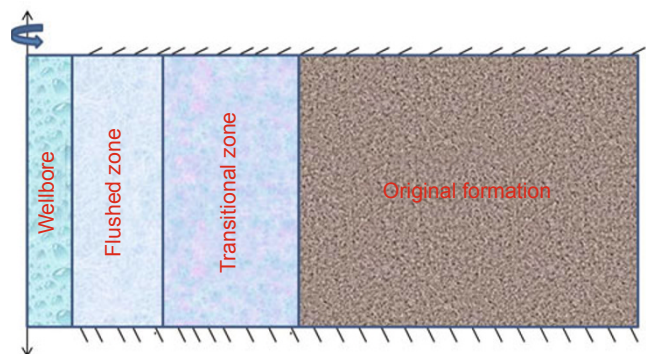


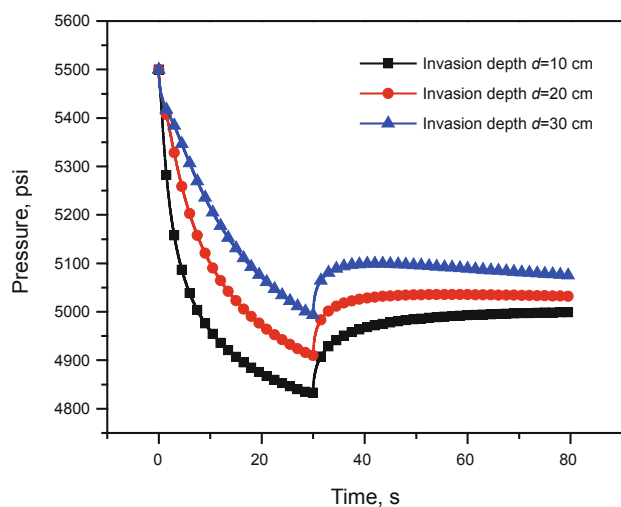
Fig. 7 Two-dimensional axisymmetric geometry for modeling filtrate invasion

Table 2 Parameters for modeling the effect of filtrate invasion

	Permeability mD	Pressure psi	Fluid density kg/m ³	Fluid viscosity mPa·s	Compressibility psi ⁻¹
Original formation	10	5000	800	1.0	3×10 ⁻⁶
Transitional zone	8.0	5300	850	0.6	3×10 ⁻⁶
Flushed zone	5.0	5500	900	0.5	3×10 ⁻⁶

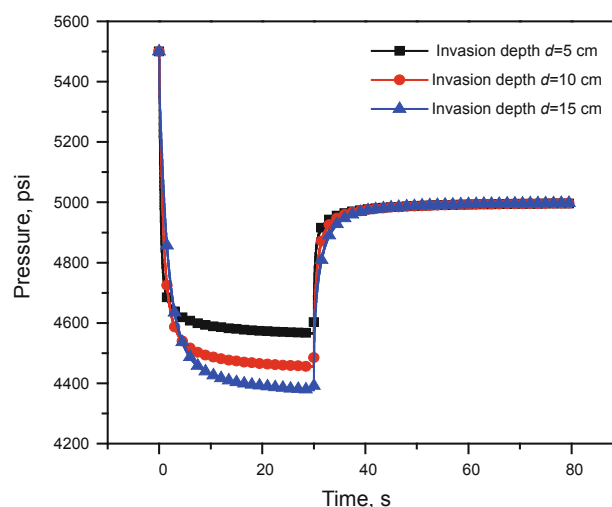
4.1 Effect of filtrate invasion on pressure testing

The impact of filtrate invasion depth on pressure testing in low permeability reservoirs was studied. The permeability values of the original formation, transitional zone and the flushed zone were set at a constant of 0.1 mD and the effect of filtrate invasion on reservoir permeability have not been considered. The other parameters are given in Table 2. Simulation results (Fig. 8) show that the draw-down pressure declines most rapidly and then recovers to the original formation pressure (5,000 psi) quickly when the filtrate invasion depth is 10 cm. However, the pressure drawdown reduces significantly and the buildup pressure maintains above the original pressure for a long time when the invasion depth increases. The reason is that the pressure of the invasion zone is higher than the original formation and the supercharge pressure cannot be balanced in a short time. Therefore, the original formation pressure may not be able to be measured in the subsequent recovery process. In these cases, it is very difficult to measure the original formation pressure in low permeability reservoirs.

**Fig. 8** The effect of mud filtrate invasion depth on pressure testing

Then we simulated the combined effect of invasion depth and change of formation permeability due to filtrate invasion. The permeability values of the original formation, transitional zone and the flushed zone were set at 10, 8 and 5 mD, respectively. The simulation results in these cases are demonstrated in Fig. 9. As can be seen, the draw-down pressure declines more quickly as the invasion depth increases. This is may be due to formation damage caused by invasion of mud filtrate, hence the permeability of the formation near the wellbore decreases. In general, the deeper

the mud invasion, the further the pressure drops. However, the pressure buildup has not changed much with different invasion depths. After 40 seconds all these curves buildup to the original formation pressure. This illustrates that the mud invasion has a slight effect on formation pressure measurements in a reservoir of moderate to high permeability.

**Fig. 9** The effect of mud filtrate invasion depth on pressure testing

4.2 Effect of filtrate invasion on fluid sampling

Finally, we studied the effect of invasion depth on fluid sampling. The initial conditions of the model were assumed as follows: the invaded zone near the wellbore is 100% saturated with mud filtrate, with a invasion depth of 10, 15 and 25 cm in the radial direction, respectively. The mudcake completely isolates the drilling fluid from the formation and the formation permeability is 10 mD. A constant pump out rate is 15 mL/s. The simulation results are shown in Fig. 10. It can be seen from this figure, as the invasion depth increases, the sample quality degrades. This is due to more time being required to clean-up the filtrate in the longer mixing zone (travel distance). Compared to the WFT, the invasion depth is much shallower when FTWD starts fluid sampling. Therefore clean formation fluids can be obtained in a relatively short period of time.

5 Field application of FTWD

The field example presented here is taken from an oil field on Alaska's North Slope. The purpose of the field test was to probe the quality of the pressure testing while drilling and the ability to repeat testing at the same points. The Geo-Tap tool

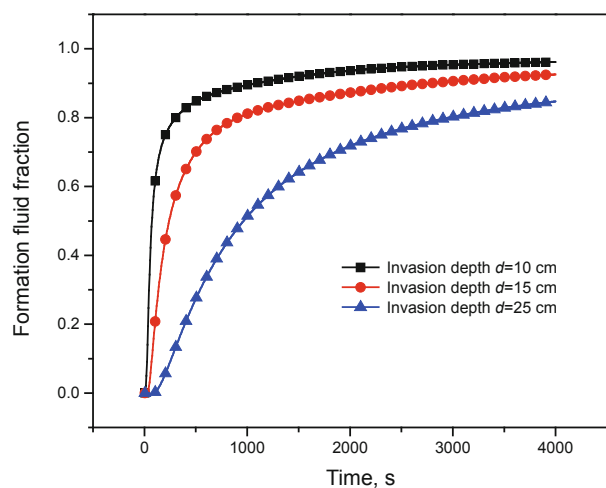


Fig. 10 The effect of filtrate invasion depth on fluid sampling

was set up with stabilizers for 9 7/8 inches in the borehole in the pumps-off mode to avoid vibration from the mud motor on the bottom hole assembly. All the pressure points were selected by the BP geologist on location while drilling the reservoir section. These FTWD (Geo-Tap) data are shown in Figs. 11 through 13.

From Fig. 11, we can see that the LWD log data for the interval from 4,150 ft to 4,200 ft suggest a mixed sand/shale sequence with thin producing layers, and the interval from

4,260 ft to 4,290 ft is a sand reservoir. The eight test positions are located at the two layers. The locations were tested from PT#1 to PT#8 where the induction log indicated potential hydrocarbons. The results of these tests are also shown in Fig. 11 and summarized in Table 3. Tool malfunction occurred during PT#2, so the formation pressure and drawdown permeability were not tested. PT#5 and PT#7 failed due to the probe being plugged. PT#1 and PT#8 were repeat tests at the same depth (4,153 ft) and the time between the two tests was 24 hours. The measured pressures were within 11 psi, the difference between the two tests was relatively small and this level of repeatability is considered quite acceptable. The detailed pressure traces from both tests are shown in Fig. 12 and Fig. 13. However, the difference of pressure repeated in PT#6 and PT#7 was 21 psi at a depth of 4,289 ft, and the time interval was 20 min, such result is not acceptable. This shows that the pressure at the location was not stable. The reason was that the reservoir permeability at this depth was very low (less than 1 mD) and therefore formation supercharging existed at a depth of 4,289 ft according to our studies. According to the above research results, Fig. 5 shows that the supercharge pressure over the original formation was more than 25 psi when the formation permeability was 1 mD, therefore the pressure was found very different between the two repeated testing due to the formation permeability being less than 1 mD, so the tested pressure was not the original pressure and the selected testing location was not appropriate.

Table 3 Modeling parameters

Test number	True vertical depth (TVD) ft	Hydrostatic pressure psi	Formation pressure psi	Drawdown permeability mD	Comments
PT#1	4153	2037	1788	40	Good test
PT#2	4171	2052	NA	NA	Tool malfunction
PT#3	4171	2050	2018	16	Good test
PT#4	4182	2088	2044	10	Good test
PT#5	4267	2125	NA	NA	Probe plugged
PT#6	4289	2139	2101	0.8	Good test
PT#7	4289	2138	2080	NA	Probe plugged
PT#8	4153	2037	1799	42	Good test

6 Conclusions

This paper analyzed the effect of the downhole dynamic environment on formation testing with an oil-water two phase finite element method. First, the paper investigated the influences of mudcake properties and formation on supercharging near the wellbore, and then investigated the influences of filtrate invasion on pressure testing and fluid sampling. Finally, the field example demonstrates the effect of downhole dynamic conditions on formation testing while drilling to support our simulations.

The simulations of formation supercharging show that the

mudcake properties have significant influence on pressure testing and fluid sampling. The better the mudcake quality is, the weaker the formation supercharge pressure and the less time is required for fluid sampling, hence the better the quality of sampling. However, the mudcake quality is difficult to determine. It is related to formation permeability and mud invasion velocity. The simulations of pressure testing and fluid sampling show that the influence of mud filtrate invasion on a low permeability reservoir is significant. The deeper the mud invasion, the more difficult the formation pressure testing and fluid sampling becomes. In addition, the depth

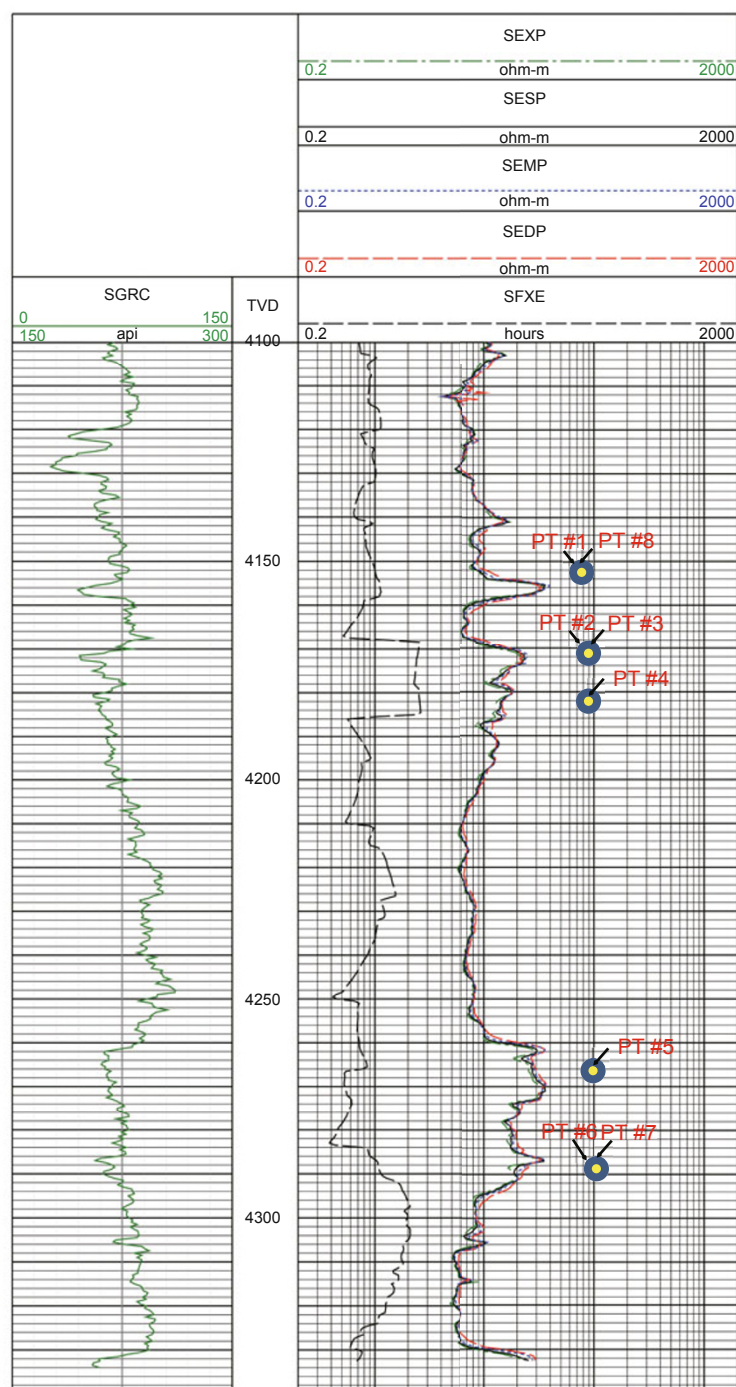


Fig. 11 LWD logs shown with Geo-Tap pressure test data for eight pressure tests
Notice the repeatability of PT#1 and PT#8 (see Figs.12 and 13 and Table 3)

of mud invasion can be estimated by the electrical logging curves, so the selection of testing locations and pressure data processing should reference the geology information and logging data while drilling.

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