Wellbore Stability in Shale Formation Using Analytical and Numerical Simulation

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Abstract

Optimization of drilling fluid parameters such as mud weight, salt concentration, and temperature is essential to alleviate instability problems during drilling through shale sections. The selection of suitable mud parameters can benefit from analyses that consider significant instability processes involved in shale-drilling–fluid interactions. This paper describes the development of analytical and numerical method for describing shale deformation. Appropriate and optimum mud pressure in which the highest consistency happens is calculated with analytical and numerical methods. It was found that, the predicted mud pressures obtained from two methods are approximately equal. The stress condition is considered non-hydrostatic. From the analytical and extensive numerical simulation it was concluded that with applying any mud pressure the well shape changes from spherical to elliptical. As the selection of the optimum mud pressure is based on the less movement and maintaining the well shape constant.

Keywords: Displacement, Mud pressure, Shale, Stress, Wellbore stability

Introduction

Wellbore stability is one of the most important factors during drilling for oil production. Shale swelling and deterioration are major sources of borehole instability and associated problems. In addition to insufficient mud weight, shale instability is significantly influenced by hydraulic and chemical gradients. When a well becomes inconsistent, collapsing can occur at one moment or in a period of time. Rise of the drilling cost is another result of wellbore instability. Shale rupture happens because of the distribution of static tension which exceeds the shear resistance and tensile strength of rock. Well consistency happens because of the principal change in mechanical tension and physical or chemical environment around the well which the formation is in contact with drilling mud.

Due to shale low permeability, the instantaneous deformation of the shale around a newly drilled borehole is likely to occur under undrained conditions. As a result, excess pore pressures will be induced in the material in response to the volume change of the rock matrix. These excess pore pressures will reduce the effective confining pressure applied on the material which will lead to a less stable wellbore condition [1-3]. The effects of volume change coefficients of the shale on critical time to wellbore failure were demonstrated through a parametric study. Swelling and hydrational stress mechanisms should be incorporated in the modeling of shale stability. The total aqueous potential of the pore fluid should be minimized/ reduced by designing drilling fluids based on the mechanisms of mud pressure penetration [4]. The mud weight preventing failure is significantly affected by drilling fluid properties. It is the most important thing for the function of drilling through the shale is to separate the contact between the shale formation and drilling mud that inhibit shale hydration when drilling mud going to shale formation [5]. The strength properties of shale can often be satisfactory estimated from previous drilling data. These estimated rock strength properties can then be used to determine the stability of highly inclined wellbores in the same area [6].

Evaluation of shale from the viewpoint of rock mechanics is a new aspect of the studies that is being developed in recent

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years. One of the most important subjects in the study of wells stability is determination of in-situ stresses. Based on performed studies, rock strength compared to other parameters such as elastic properties of the rock, drainage conditions and stratification plates is more important in the wellbore stability [7,8]. When a vertical well within the normal fault stress regime ($\sigma_v>\sigma_H>\sigma_h$) is drilled, the well remains stable. Under conditions of strike-slip fault stress ($\sigma_H>\sigma_v>\sigma_h$), horizontal and decline wells are more stable than vertical wells [9].

During the drilling of shale layers wellbore stability could be analyzed by use of numerical and analytical methods and also considering the reasonable and proper parameters and reduce costs resulting from the wellbore instability with correct understanding. This research will also regard to effects of physical and mechanical properties of shale on wellbore stability of oil wells in one of the Iran oil fields. In addition, one of these situations that is correspond to the situation of desired well was investigated by numerical method and optimum mud weight for that depth was suggested and then the results of analytical and numerical (finite difference) methods were compared. Results indicated that awareness of the status and value of in-situ stresses has great effects on the analyses.

2. Methodology

A cross section at a depth of 3486 m of the well within the desired shale layer of Ilam formation was considered to evaluate the wellbore stability in Ahwaz oilfield by numerical and analytical methods. Well diameter in this section is 8 3/8 inch and mud cake thickness is about 1.35 inch. Density of drilling mud to maintain the stability is 82 to 83.3 pounds per cubic foot and the pore pressure has been measured about 42.6 MPa. In this depth shale instability is the type of well narrowing.

3. Analytical Method

To determine the allowable mud weight, the generalized Mohr - Coulomb failure criteria was considered. Vertical stress is obtained according to the rock type from the average rock density that is presented in the different texts. Based on the average density of petrology column of desired wells, the vertical stress (S_v) was 93 MPa at a depth of 3486 meters. To obtain the minimum and maximum horizontal stresses ($S_{H,\ max}$, $S_{h,\ min}$) and prediction of difference stress range Anderson faulting theory was used to determine the stress regime. The minimum and maximum horizontal stresses for the different scenarios can be calculated by the following equations. Respectively by assuming the normal and reverse faulting modes, Eq. 1,2 are as follows:

In the above equations P_0 is pore pressure, σ_1 and σ_2 are maximum and minimum original stresses, and μ is a constant that is considered to be equal to 0.6 here. It is assumed that the stress status within the crust is in frictional equilibrium. Placing the values (42 MPa for pore pressure) in the above equations gives the normal reverse faulting:

In these equations S_1 and S_3 are the vertical and horizontal stresses. With assumptions that $S_{h\ min}$ is the vertical line and $S_{H\ max}$ as horizontal line, stress polygon could be plotted for the desired depth. This polygon defines possible amount of minimum and maximum original stresses at any depth based on Anderson faulting theory and also Mohr -Coulomb faulting theory with a friction coefficient and pore pressure. In the Figure 1 this stress polygon has been plotted and presented.

Zimmerman and Al-Ajmy [10] by using Mohr - Coulomb failure criterion related to the well and kirsch equations, have obtained equations to calculate the upper and lower bound of mud pressure. These equations have been presented in Tables 1 and 2.

$$\frac{\sigma_1}{\sigma_3}=\frac{S_v-P_0}{S_{h,min}-P_0}\le\left[(\mu^2+1)^{\frac{1}{2}}+\mu\right]^2 \quad (1)$$

$$\frac{\sigma_1}{\sigma_3}=\frac{S_{h,max}-P_0}{S_v-P_0}\le\left[(\mu^2+1)^{\frac{1}{2}}+\mu\right]^2 \quad (2)$$

Table 1: Mohr - Coulomb criteria for collapse pressure in vertical well

status	$\sigma_3 \leq \sigma_2 \leq \sigma_1$	If $P_w \leq P_{wb}$, well will collapse.
1	$\sigma_r \leq \sigma_{\square} \leq \sigma_z$	$P_{wb1} = (B-C) / q$
2	$\sigma_r \leq \sigma_z \leq \sigma_{\square}$	$P_{wb2} = (A- C) / (1+ q)$
3	$\sigma_z \leq \sigma_r \leq \sigma_{\square}$	$P_{wb3} = A- C- qB$

Table 2: Criteria Mohr - Coulomb for wellbore flowing pressure in vertical well

status	$\sigma_3 \leq \sigma_2 \leq \sigma_1$	If $P_{wf} \leq P_w$, well will fail.
1	$\sigma_z \leq \sigma_{\square} \leq \sigma_r$	$P_{wf1} = C+ qE$
2	$\sigma_{\square} \leq \sigma_z \leq \sigma_r$	$P_{wf2} = (C+ qD) / (1+ q)$
3	$\sigma_{\square} \leq \sigma_r \leq \sigma_z$	$P_{wf3} = (C- E) / q+ D$

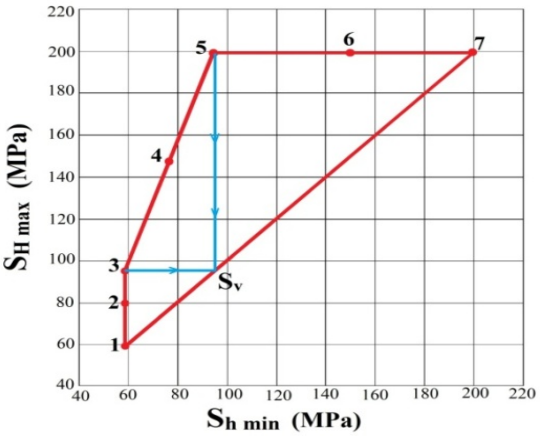

Figure 1: Polygon stress for depth of 3486 m and pore pressure of 42 MPa

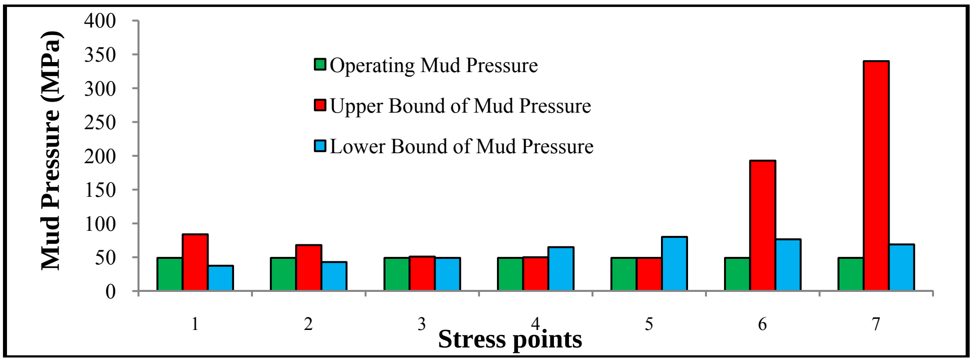

Figure 2: Lower and upper bounds of mud pressure for each of the stress states

Optimum mud weight in a vertical well could be determined with calculating the values of collapse and failure pressure and according to the stresses status. Well will collapse if the calculated values of the collapse pressure (P_{wb}) are more than the value of practical mud pressure in the desired well. Likewise if the calculated values of failure or wellbore flowing pressure (P_{wf}) are less than practical mud pressure, well will fail. In the Tables 1 and 2, σ_r, σ_Z and σ_Θ are stresses resulting in the wellbore; P_w is internal well pressure and parameters, A, B, C, D, E and q are:

$$A = 3\,\sigma_H - \sigma_h \tag{3}$$

$$B = \sigma_b + 2\upsilon(\sigma_H - \sigma_h) \tag{4}$$

$$C = C_0 - P_0\,(q - 1) \tag{5}$$

$$D = 3\,\sigma_H - \sigma_h \tag{6}$$

$$E = \sigma_r - 2\upsilon\,(\sigma_H - \sigma_h) \tag{7}$$

$$q = \tan^2\left(\frac{\pi}{4} + \frac{\varphi}{2}\right) \tag{8}$$

In the above equations, σ_H and σ_h are respectively maximum and minimum horizontal in-situ stresses, υ Poisson's ratio, φ internal friction angle of rock and C_0 is:

$$C_0 = \frac{2c\mathrm{Cos}\varphi}{1 - \mathrm{Sin}\varphi} \qquad (9)$$

According to the diagram of stress polygon, we can assume seven points with specific stress statuses in the desired section. For each of these scenarios upper and lower bounds of mud pressure according to the equations of Mohr-Coulomb failure criterion could be calculated. In each of these in-situ stress statuses, two values could be calculated, the first upper bound of the mud pressure or P_{wf} and second lower bound or P_{wb}. For wellbore stability mud pressure should be between these two limits, in other words: $P_{wb} \leq P_w \leq P_{wf}$.

The diagram that has been obtained by using these mentioned equations is presented in the Figure 2. Comparing the graphs of lower bound of mud weight and used mud weight in the Figure 2 make clear that in point 1, with the current in-situ stresses status, will not occur any falling in the well, but in other points may well be collapsed. Likewise comparing the graphs of upper bound of mud weight and used mud weight show that in the points of 1, 2, 6 and 7 well will not fail but in the points of 3, 4, and 5 mud weight almost is equal to the upper bound of mud weight and this can cause well failure.

4. Numerical method

In this study, simulation operation of consistency of wellbore is examined with finite difference method. Analyzing the consistency depends on many parameters like well shape, formation fluid pressure, in situ main forces, and mechanical properties of the rock and mud weight. Among these parameters the only parameter which is controllable is mud weight. Optimization of specific weight is important because it is an essential factor in formation fracturing control and drilling mud loss. Mud pressure should be designed in a way that it becomes lesser than formation fracture pressure and more than fluid pore pressure. Considering these conditions, the formation does not break and fluid loss and pipe sticking won't happen and mud pressure can prevent the fluid from entering the well and control the model is a cylinder which the well is at the center of it and the dimension of the block is 20*20. For numerical analyzing of the data, we need the geo mechanical characteristics of shale layer which is given in Table 3. In the provided model, the tension in x and y directions are not equal and the condition is not isotropic. In other words the condition of static tensions is non-hydrostatic. In here the Burger creeping model is used. If we assume that the drilled well is without the drilling mud, then there is no preventing factor for entering the shale to well.

Table 3:Mechanical and physical properties of the shale layer

(	*C(MPa)*	Specific weight (Kg/m^3)	σ_c *(MPa)*	$\upsilon_2 = \upsilon_3$	υ_1	$E_2 = E_3$ *(GPa)*	E_1 *(GPa)*	Type of rock
50	13	2500	80	0.1675	0.43	8	14	Limestone shale

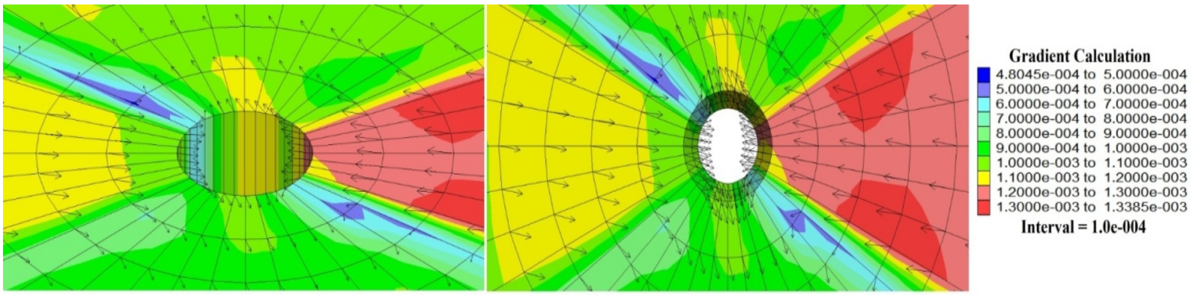

Figure 3:Direction of displacement of shale formation when a mud with 50 MPa pressure is in the well

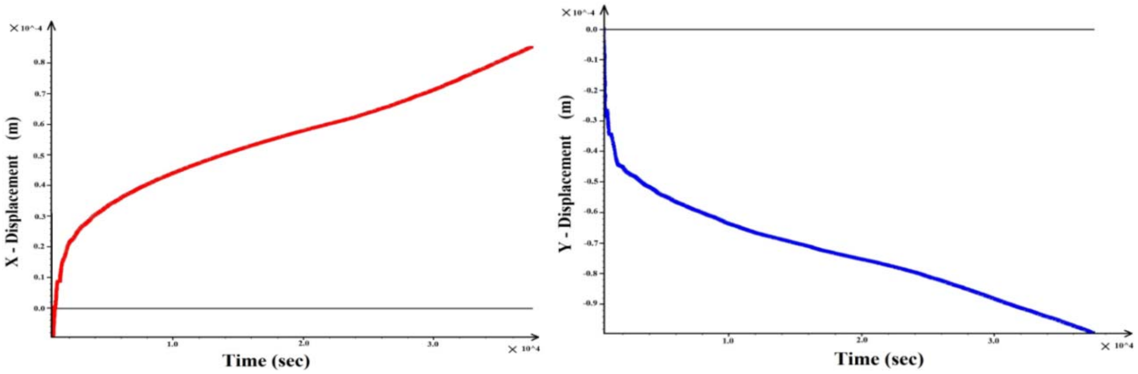

Figure 4:Formation displacement in x and y direction in presence of a mud with 50 MPa pressure

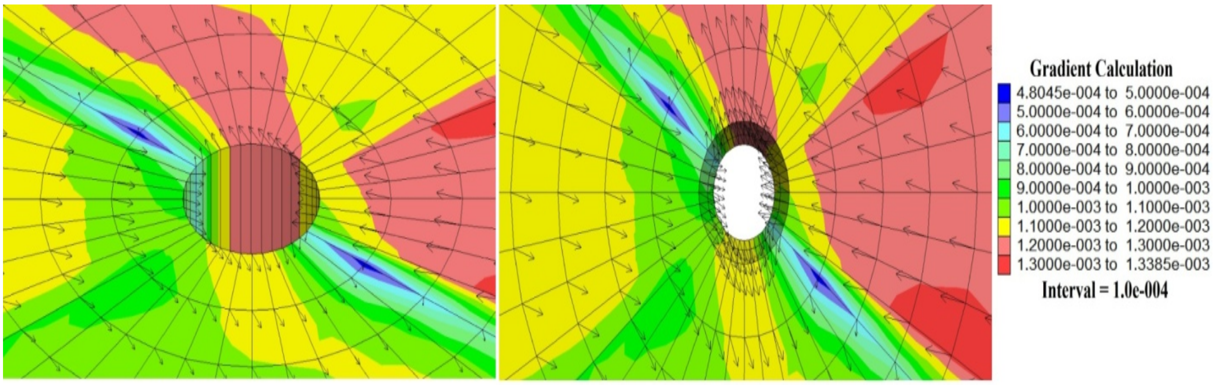

Figure 5: Direction of shale formation displacement when pressure of mud in the well is 60 MPa

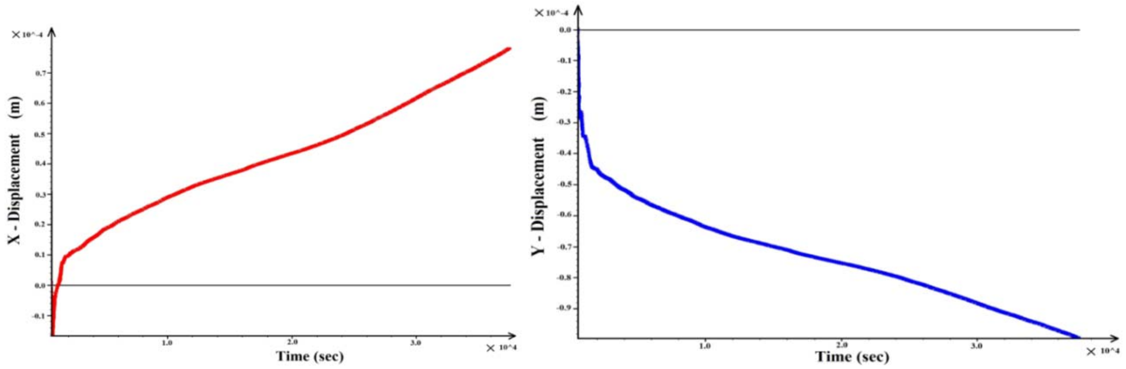

Figure 6: Formation displacement in x and y direction with 60 MPa mud pressure

Now we consider drilling mud with different weights and in each stage the consistency of well is analyzed. Here the mud weight is the only parameter that changes and the other parameters are considered to be constant. The mud pressure is considered 50 MPa. The reason is that the pore pressure is equal to 42.6 MPa therefore the mud pressure should be more than this amount. As it is seen in Figure 6, when the mud pressure is 50 MPa, the formation enters the well from x direction because the pressure in the x direction is more than the mud pressure. On the other hand the formation is pushed back in y direction because the mud pressure practically pushes it back. The directions shown in Figure 3 display the displacement vectors. Amount of displacement in x direction into the well after 11 hours is approximated as 0.1022 cm and this amount of displacement in y direction is about -0.09842 cm. Amount of displacement in x and y directions are shown in Figure 4.

In the next step the mud pressure is increased to 60 MPa. The direction of displacement and amount of displacement are shown in Figures 5 and 6. In this condition the amount of displacement in x direction is 0.0784 cm and in y direction -0.09947. If we pay attention to Figure 3 and 4, it can be seen that the amount of displacement is decreased. This means that when the mud pressure is equal to 60 MPa, the well shows a better consistency compared with mud pressure of 50MPa.

This time for the mud pressure of 70 MPa, the direction of displacement in x and y directions are shown in Figure 7. The amount of displacement is 0.06384 cm in x direction and -0.0939 cm in y direction (Figure 8).

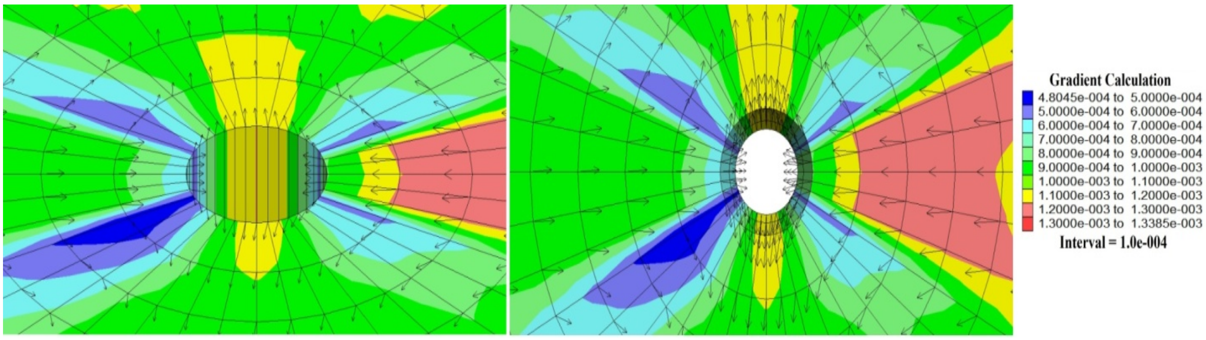

Figure 7:Direction of formation displacement with mud pressure of 70 MPa

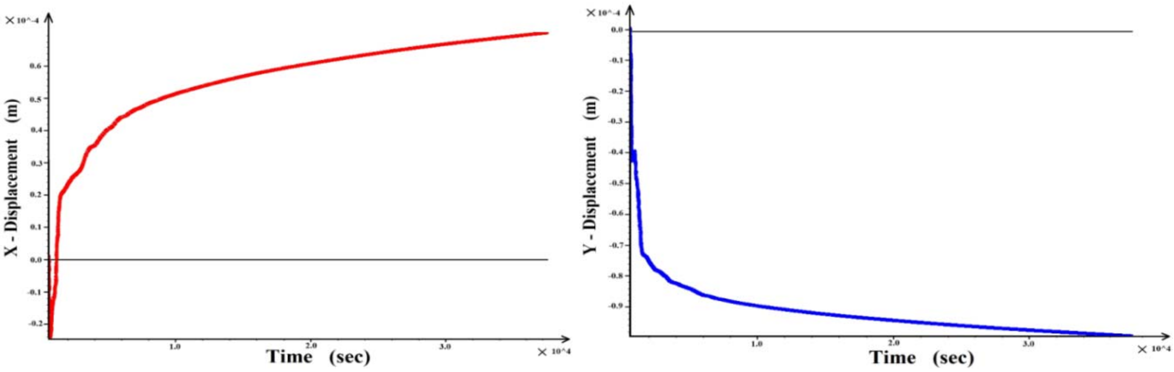

Figure 8:Formation displacement in x and y direction with mud pressure of 70 MPa

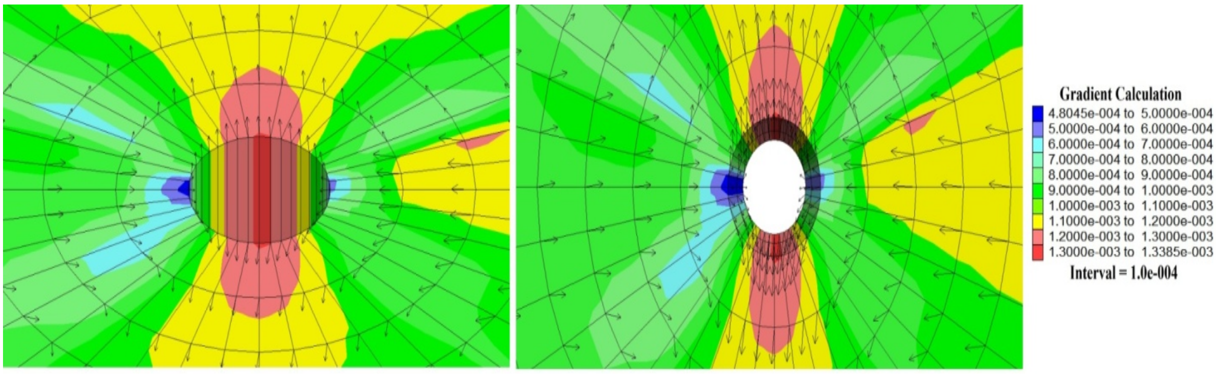

Figure 9: Direction of shale formation displacement when a mud with 80 MPa pressure is present

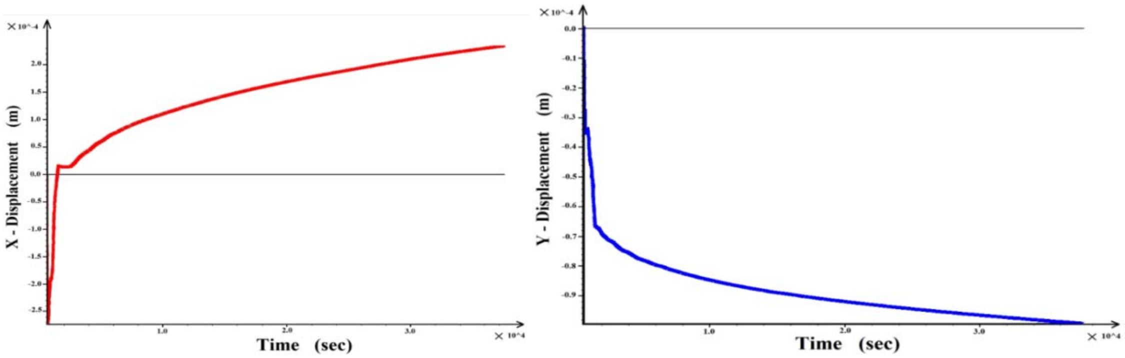

Figure 10:Displacement of formation in x and y direction in presence of a mud with 80 MPa pressure

Table 4: Formation displacement X and Y direction at between 70 MPa and 80MPa

Mud pressure [MPa]	Displacement in x direction [cm]	Displacement in y direction [cm]
71	0.05733	0.09398-
72	0.04783	0.09403-
73	0.03752	0.09411-
74	0.03533	0.09764-
75	0.03477	0.09789-

In the next step mud pressure is considered to be 80 MPa. This time the condition is different because the displacement contours in x duration decrease and in y direction increase (Figure 9). The amount of displacement in x direction is 0.02726 cm and in y direction -0.1002 cm (Figure 10). As it was seen with increasing the mud pressure to 80 MPa practically the displacement in y direction increases therefore it could be concluded that approximately the best condition for drilling mud is between 70 MPa and 80 MPa. So, the optimum pressure is selected between these two pressures and the results are shown in Table 4.

According to the results, least average displacement in x and y direction happens when the drilling mud has 73 MPa pressure. A schematic of well and shale formation displacement when the mud pressure is equal to 73 MPa can be seen in Figure 11. Displacement in x and y directions can be also seen in Figure 12. The critical time to failure is defined as the time for extent of instability to occur around the wellbore which resulted in numerical (computational) instability due to excessive number of yielding (failing) elements. It can be seen that the critical time to failure increases greatly with the increase of the mud weight.

Of course this increase in mud weight causes an increase in consistency time of wellbore up to an optimum point (73 MPa). The results show that swelling mechanism has very significant effects on time-dependent wellbore instability. The rock material away from the borehole will be restrained from swelling freely. This would result in the generation of hydrational stress which will induce pore pressure and total stress changes based on poroelastic properties of the rock material and pore fluid. The induced pore pressure will further increase the pore pressure in the formation which reduces the effective mud support and leads to a less stable well bore condition.

The main aim of increasing the mud pressure is to neutralize the pore pressure but that is induced by shale formation property. As it was seen, with increasing the mud pressure, the consistency of well decreased because the amount of shale formation displacement decreased. However, the optimum mud pressure in this study was 73MPa and with increasing the mud pressures the total displacement or average pressure increased in x and y directions. With increasing the mud pressure from 73 MPa, the amount of displacement in x direction decreased but for y direction it increased. The reason for selecting 73 MPa pressure for optimum mud pressure for well consistency is that the well shape remains circular. The reason is that the amount of displacement in x and y direction is minimum and the well shape is circular and according to the results the mud pressure of 73 MPa is minimum. Created models show that the circular well shape cannot be maintained and the wellbore consistency cannot be demolished.

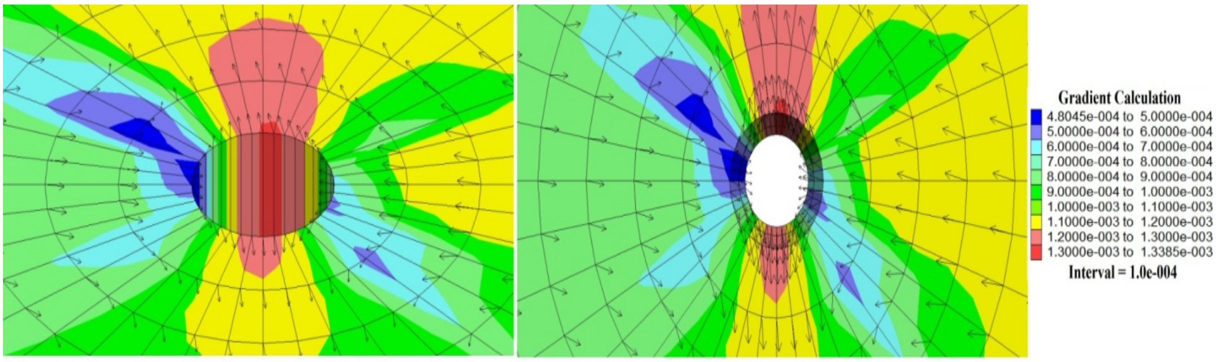

Figure 11: Direction of displacement of shale formation when a mud with 73MPa pressure exists in well

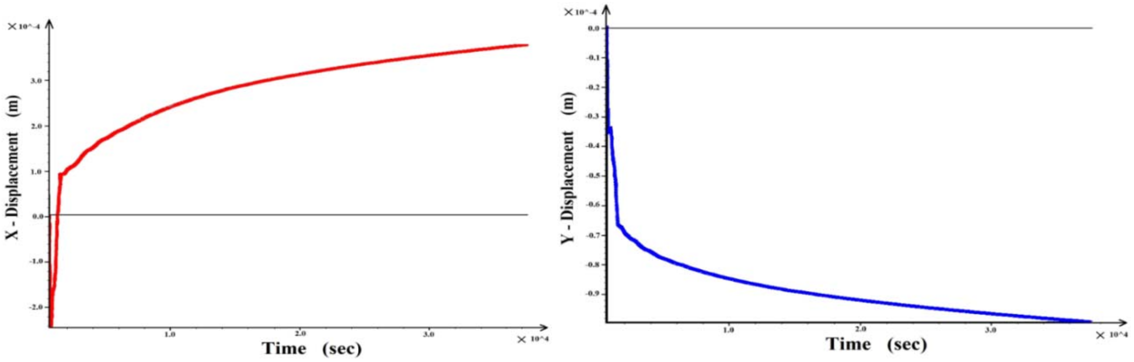

Figure 12: Formation displacement in x and y direction in presence of a mud with 73MPa pressure

5. Conclusion

For consistency of the wellbore, the amount of mud pressure should be between the collapse pressure and formation break pressure. Because of the absence of field data, the amount and condition of in-situ stresses were calculated with Anderson theory and drawing tension polygon. In this study with the use of Mohr-coulomb fracturing basis, generalized for the well, the allowable range of weight (mud window) and upper and lower limit of mud for different cases of tensions from polygonal faulting and frictional stress was obtained. From the analyses, the amount of mud pressure which causes the consistency for the well was obtained. The results from the finite difference method were closer to reality and also the analytical solution.

Time-dependent wellbore instability management and optimum drilling fluid design in terms of mud type, weight, chemistry and temperature can be facilitated by using numerical modeling that couples all the key time-dependent drilling fluid-shale interaction processes to mechanical stability analysis. The optimization of the drilling fluid design can mitigate time-dependent wellbore instability in shale. The choice of optimum drilling fluid characteristics depends on the formation properties, temperature, in-situ stresses and wellbore trajectory. The analysis of time-dependent wellbore stability in shales requires modeling of various couple processes that are dependent on the relative properties of the drilling fluid and formation.

As it is mentioned in this study only the mud pressure is studied for consistency of wellbore. But using cold mud or mud with high salt can increase consistency. In other words two physical and chemical conditions should be both evaluated in shale formations. For physical analysis, the most optimum mud pressure which causes the least deformation of well and least displacement in wellbore should be selected. When the tensions are not hydrostatic, the prevention of converging wellbore is not possible and with designing an appropriate fluid the well radius can be maintained.

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