Prediction of the Optimal Drilling Mud Weight Based on the Normalized Yielded Zone Area (NYZA) in One of the Iranian Oil Fields

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Abstract

Hole problems experienced during the drilling phase of operations are often the consequence of mechanical wellbore instability. This leads to higher than necessary drilling costs. The only controllable factor that can prevent wellbore instability is the drilling mud. In this study, the optimal drilling mud weight to prevent instability using the Finite Element Method (FEM) was simulated in one of the fields of Southwest Iran. To determine the optimal drilling mud weight, the various hydrostatic pressure equivalents to mud weight were applied and plastic strains and stresses were obtained and analyzed. The obtained results from the predicted mud weight using FEM appeared to have a 0.14 % error with the reported drilling mud weight, which shows a good agreement between the obtained simulated results and field evaluations.

Keywords: Stability, optimum mud weight, finite element, plastic strain, Drucker-Prager criterion

Introduction

Wellbore stability, in terms of analysis and prediction, is considered to be a critical problem in well drilling operations. Instability leads to wasting much time and money in all areas of the world. Therefore, analysis and prediction of wellbore stability are of utmost importance. The stability of a well depends on various factors, such as drilling trajectory, geometrical shape and azimuth of the well, in situ stresses, pore pressure, chemical and mechanical properties of rock, and mud weight [1,2]. Obviously, the only controllable factor is the drilling mud. Ezzat [3] discussed different laboratory tests performed for suitable mud design for drilling in Khafji and other reservoirs in Saudi Arabia; moreover, he showed that it is not possible to propose a specific mud for different cases, due to the various geological conditions, and the mechanical and chemical properties of rocks. Santarelli *et al*. [4] presented wellbore instability problems occurring in a developed field in Italy. The problems were back analyzed with respect to the mud types, mud weights, azimuths, and stress regime. They found that most of the drilling problems, such as stuck pipes, occur at a particular azimuth. Onaisi *et al*. [5] predicted the mud weight required to prevent instability through mechanical simulation of rock. They showed that the predicted mud weight by this method is more than the mud weight which is used during the drilling operation. Mohiuddin *et al*. [6] predicted mud weight with 90 % confidence through the analysis of instability in vertical, directional, and horizontal wells by using field data and instability mechanisms and the problems arising from them, such as stuck pipes. Morshedi *et al*. [7] studied the stability of the wells in one of the fields of southwest Iran using the Finite Difference Method (FDM). They predicted the optimal mud weight with 0.43 % error, compared with the reported mud weight. The performed analysis on one well is no longer used for other wells due to the geology and petrology differences among wells.

The stability of the well and the optimal mud weight should be determined based on the specific characteristics of each well and through the best method. In this paper, stability in different values of mud weights has been studied using the Finite Element Method (FEM) in which geological characteristics, mechanical properties of rock, pore pressure, and stress distribution are considered, in order to more accurately determine the optimal mud weight. Finally, the results are compared with the results obtained from FDM.

Materials and methods

In this study, modeling was done using Finite Element Analysis (FEA). FEA is a tool to better understand how a design will perform under different sets of impacts or stresses in certain conditions. FEA is a computer-based mathematical representation method of solving problems numerically. Since this is a numerical solver, the answer is not exact. It works on the basis of material properties, type of model, and boundary conditions. Since FEM is a simultaneous multi-partial-differential equations solver, it is a time saving method. Finite Element can handle complex boundary conditions, which is the reason this type of programming is still used for investigating problems more realistically than the FDM can provide [8-10].

In this study, three-dimensional modeling has been used to investigate stability under different values of mud weight and the optimal value of mud weight in the studied well, located in one of the fields of southwest Iran. Modeling has been done at a depth of 3698-3703 m. The height of the model is 5 m and its length and width is 5 times the radius of the open hole well. The model is divided into 8 parts in the x and z direction and 17 parts in the y direction, and the circumference of the well has been divided into 32 parts. The element of solid95 has been used for the analysis of the model. This element consists of 20, nodes and there are three degrees of freedom in each node. This element may have any spatial orientation and has plasticity, stress stiffening, large deflection, and large strain capabilities, due to the existence of axially symmetrical geometry. Only one quarter of the model is considered to reduce the computations needed (**Figure 1**). Mechanical properties of the rock, stress values, and the geometric characteristics of the well are listed in **Table 1**. Except for the deviation angle and diameter of the well, all values listed in **Table 1** are average values.

Table 1 Information of the well and rock.

Parameter	Value
Well diameter (inch)	7
Young's modulus (GPa)	20
Cohesion (MPa)	5
Angle of internal friction (degree)	29.3
UCS (MPa)	17.08
Vertical stress (MPa)	84.3
Maximum horizontal stress (MPa)	73.96
Minimum horizontal stress (MPa)	63.2
Pore pressure (MPa)	39
Density (kg / m^3)	2280
Deviation angle (degree)	0

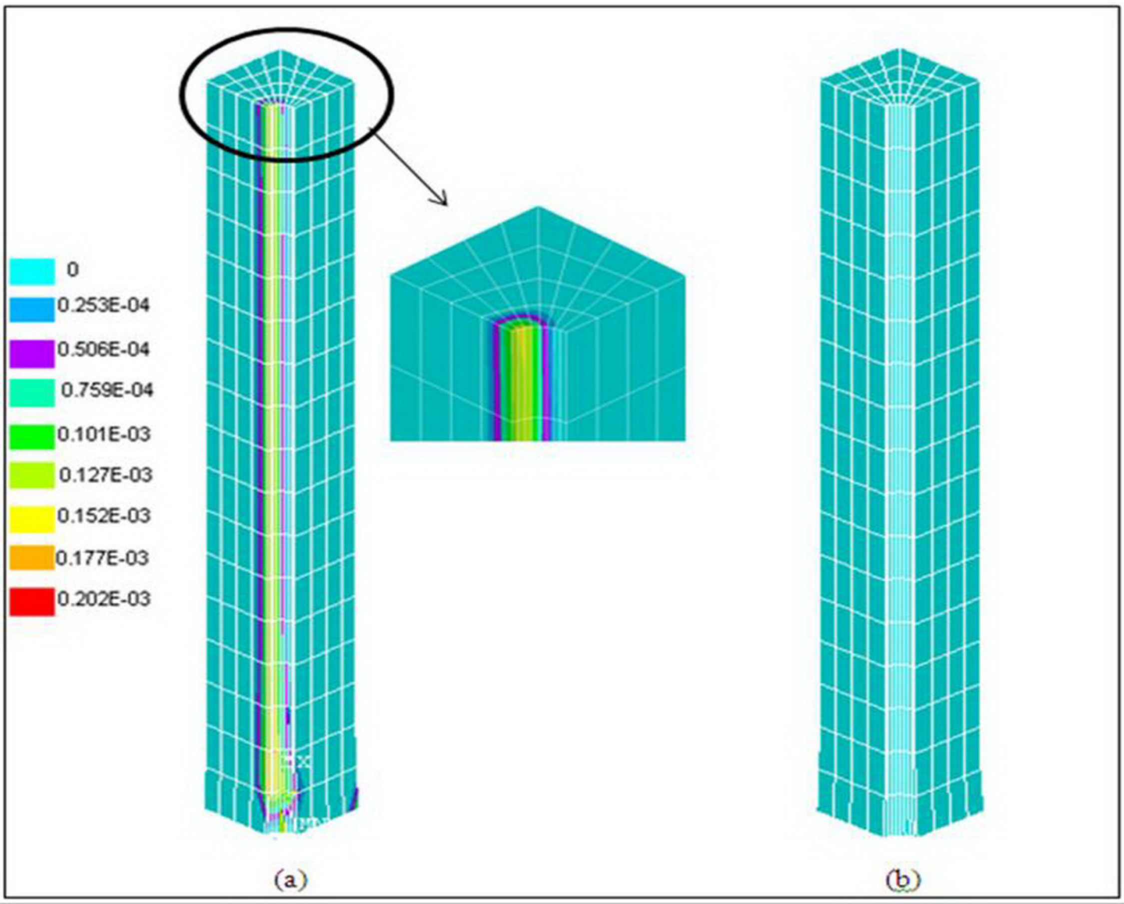


Figure 1 The geometry of the model and the condition of generated plastic strain in the wellbore with (a) no drilling mud and (b) MW = 68.4 PCF.

In this study, the stability criterion is based on the stress ratio and the value of the developed plastic strain in the wellbore. The Drucker-Prager yield criterion is used to investigate plastic strain. In this criterion, yield surface will not change by increasing yield, so there is no hardening rule, and the material is elastic-perfectly plastic [10]. In this case, the equivalent stress and the yield stress are obtained from Eqs. (1) and (2), respectively.

$$\sigma_e = 3\beta\sigma_m + [0.5\ \{S\}^T\ [M]\ \{S\}]^{0.5} \tag{1}$$

where

$$\sigma_m = \frac{1}{3}(\sigma_x + \sigma_y + \sigma_z)\ ,\ S = \sigma - \sigma_m \ \text{ and } \ \beta = \frac{2\ sin\varphi}{\sqrt{3}\ \ (sin\varphi)}$$

$$\sigma_y = \frac{6C.\cos\varphi}{\sqrt{3}\,(3-\sin\varphi)} \tag{2}$$

$\{S\}^T$is the deviatoric tangential stress, and {S},φ and C are the deviatoric stress and friction internal angle and cohesion, respectively. [M] is defined using Eq. (3).

$$\sigma_e = [1.5\ (\{S\} - \{\alpha\})^T[M](\{S\} - \{\alpha\})]^{0.5} \tag{3}$$

$$\{\alpha\} = \int c_1\ \{d\varepsilon^{pl}\}$$

c_1 and ε^{pl} are the material parameter and plastic strain, respectively. Eq. (3) is the equivalent stress of Von Mises yield criterion. The Drucker-Prager yield criterion is a modification of the Von Mises yield criterion that accounts for the influence of the hydrostatic stress component: the higher the hydrostatic stress (confinement pressure) the higher the yield strength. The yield criterion is defined as Eq. (4).

$$F = 3\beta\sigma_m + [0.5\ \{S\}^T\ [M]\ \{S\}]^{0.5} - \sigma_y = 0 \tag{4}$$

The stress ratio, N, is the equivalent stress to the yield stress given in Eq. (5).

$$N = \frac{\sigma_e}{\sigma_y} \tag{5}$$

If the equivalent stress is less than the yield stress (N is less than 1), the material will be in elastic mode; if the stress ratio (N) is equal to or greater than 1, the material is in the yield mode [10,11]. In the whole analyses, the stress ratio was calculated, which shows that there is less stress ratio at the optimum mud weight (**Table 2**), due to the wellbore stability situation.

Table 2 The results of the stress ratio and plastic strain on the wellbore wall at different values of mud weight.

Hydrostatic pressure equivalent to mud weight (MPa)	Mud weight (PCF)	Plastic strain (*10^-6)	Stress ratio
0	0	119	13.274
10	17.208	89.2	10.188
20	34.41	59.04	7.082
30	56.25	28.69	3.956
38	65.39	3.42	1.353
39	67.11	1.446	1.149
39.5	67.97	0.458	1.047
39.70	68.31	0.225	1.007
39.75	68.4	0	0.996
39.8	68.5	0	0.986
40	68.83	0	0.945
48	82.56	0	0.866
48.5	83.42	0	0.925
48.8	83.93	0	0.963
49	84.28	0	0.988
49.10	84.45	0.652	1.001
49.11	84.47	1.773	1.002
49.12	84.48	2.895	1.003
49.13	84.50	4.0161	1.005
49.14	84.52	5.138	1.006
49.15	84.54	6.261	1.007

Results and discussion

To investigate the stability analysis under different values of mud weight and to determine the optimal mud weight, the hydrostatic pressure equivalent to mud weight was applied and developed plastic strains and stresses were obtained and analyzed. **Figure 1a** illustrates the condition of generated plastic strain in the wellbore when there is no drilling mud in the well. Mud weight acts as a factor against in situ stresses and pore pressure, and its increase to the optimum reduces the plastic strain [12]. **Figure 2** shows plastic strain changes for different amounts of mud weight from the wellbore wall to the external boundary of the system. **Figure 2** illustrates that only 16.9 cm from the well center is located in the yield area. When the mud weight increases, the amount of plastic strain in the yield area drops, so that mud weight equal to 68.4 pound per cubic feet (PCF) will reach zero. **Figure 3** shows the effect of mud weight on the created plastic strain in the wellbore wall for different amounts of mud weight. Stress ratio (N) is the ratio of equivalent stress to yield stress. According to Eq. (2), yield stress is based on the mechanical properties of the rock and is constant (assuming neither the temperature of the drilling mud nor chemical reactions between the drilling mud and rock have a significant effect on the mechanical properties of rock). According to Eq. (1), the equivalent stress is the function of *in situ* stresses; on the other hand, drilling mud is a resistant agent and reduces the effect of stresses on the wellbore, thus decreasing the equivalent stress. Therefore, due to increasing the mud weight to the optimum value, the stress ratio reduces. Mud weight should be a sufficient enough factor to enable the wellbore wall to be in the elastic mode and for the amount of stress ratio in the wellbore wall to be less than 1.0. **Figure 4** shows the effect of increasing mud weight on the amount of stress ratio on the wellbore wall. The results of the stress ratio and plastic strain on the wellbore wall at different values of mud weight are briefly listed in **Table 2**. Determined optimal mud weight obtained from numerical simulations and the reported mud weight from drilling operations are listed in **Table 3**.

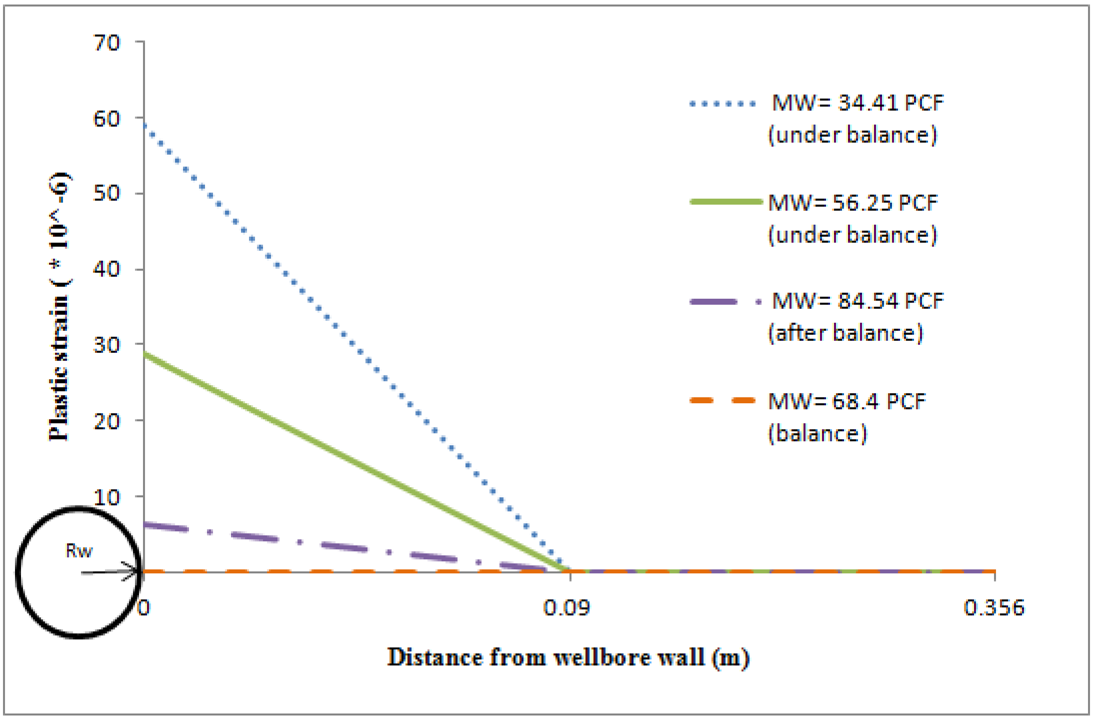
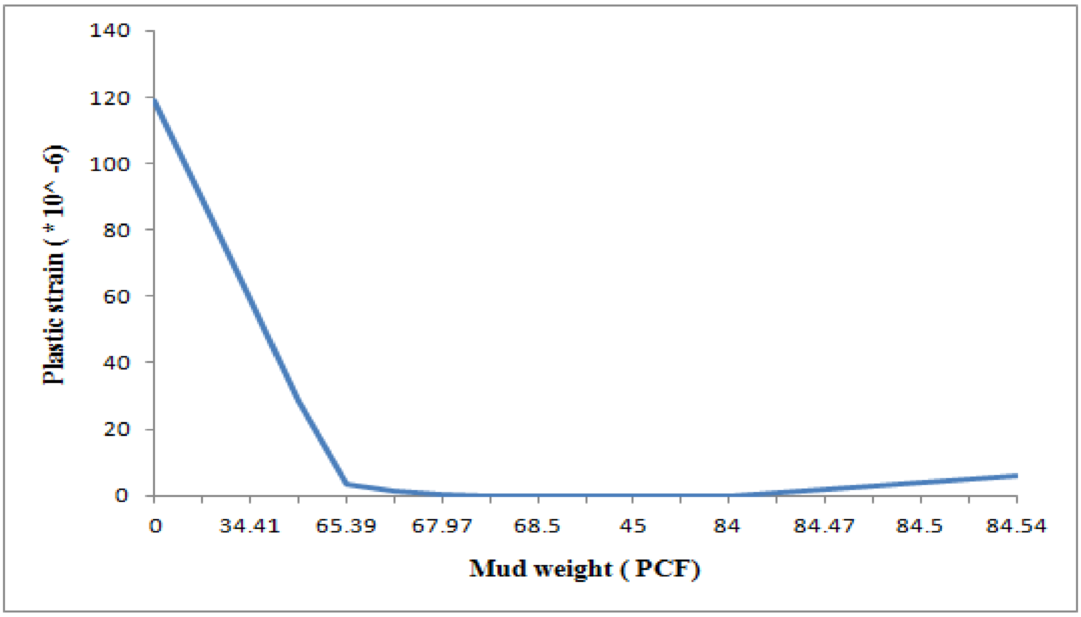


Figure 2 Plastic strain changes for different values of mud weight from the wellbore wall to the external boundary of the system.



Figures 3 The effect of mud weight on the developed plastic strain in the wellbore wall for different amounts of mud weight.

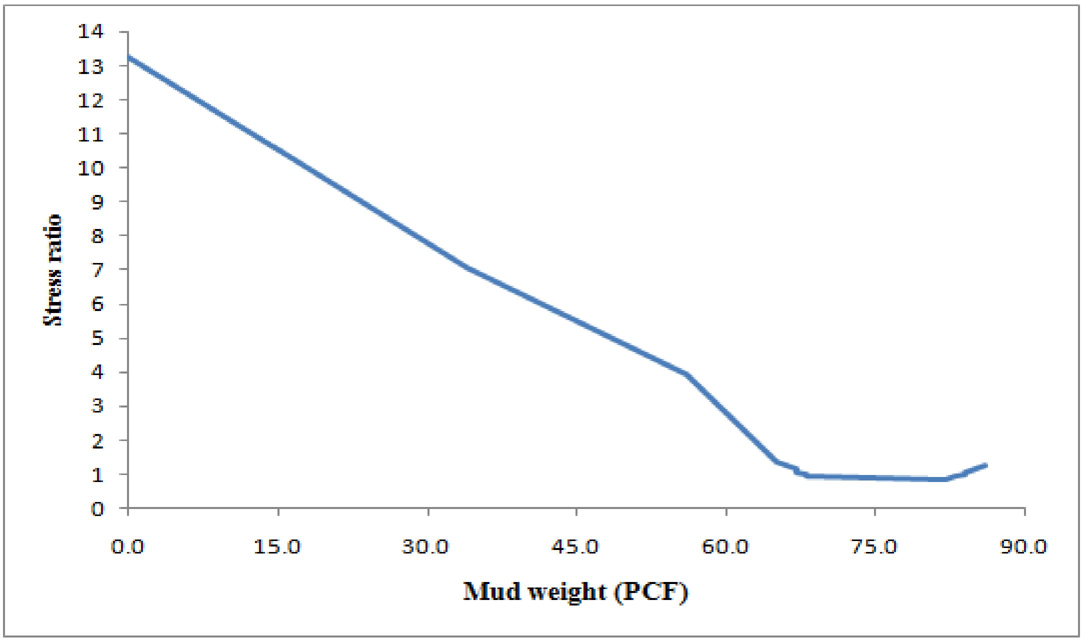


Figure 4 The effect of increasing mud weight on the amount of stress ratio on the wellbore wall.

Table 3 The optimal mud weight obtained from FEM and FDM and reported from drilling operations, and the error of each method compared with the reported mud weight from drilling operation.

Method	Predicted mud weight (PCF)	Error (%) (compared with reported MW)
FEM	68.4	0.14
FDM	68.8	0.43
Reported from drilling operation	68.5	-

A parameter often used as a borehole instability risk indicator is the Normalized Yielded Zone Area (NYZA), which is the cross-sectional area of the yielded rock around the borehole divided by the area of the original borehole [12]. Experience has indicated that the onset of borehole instability problems is often associated with NYZAs greater than 0.08. **Figure 5** shows the trend of NYZA changes with mud weight. As shown in **Figure 5,** with increasing mud weight, the NYZA will decrease and allow for a more stable wellbore. Typically, drilling with a bottom hole pressure above the formation pore pressure will decrease the risk of borehole instability, due to less yielding area of the rock adjacent to the borehole. Figure 5 indicates that there is a relatively small amount of yielding (NYZA less than 0.08) predicted for pressures less than reservoir pore pressures. In this field mud weight ranges from 65.876 - 67.08 PCF considering the under balanced drilling (UBD) condition would be acceptable.

The relationship between NYZA and mud weight is shown in **Figure 6**. It shows that the relationship between the NYZA and the mud weight is a linear relationship with correlation equal to 0.9776.

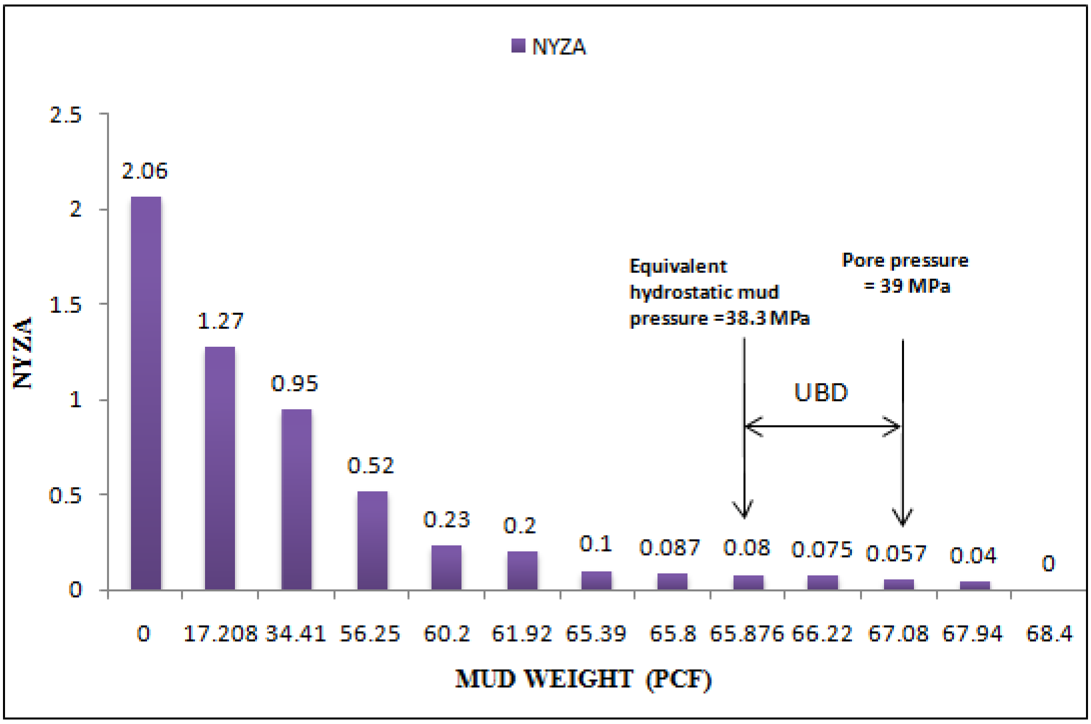


Figure 5 The trend of NYZA changes with mud weight.

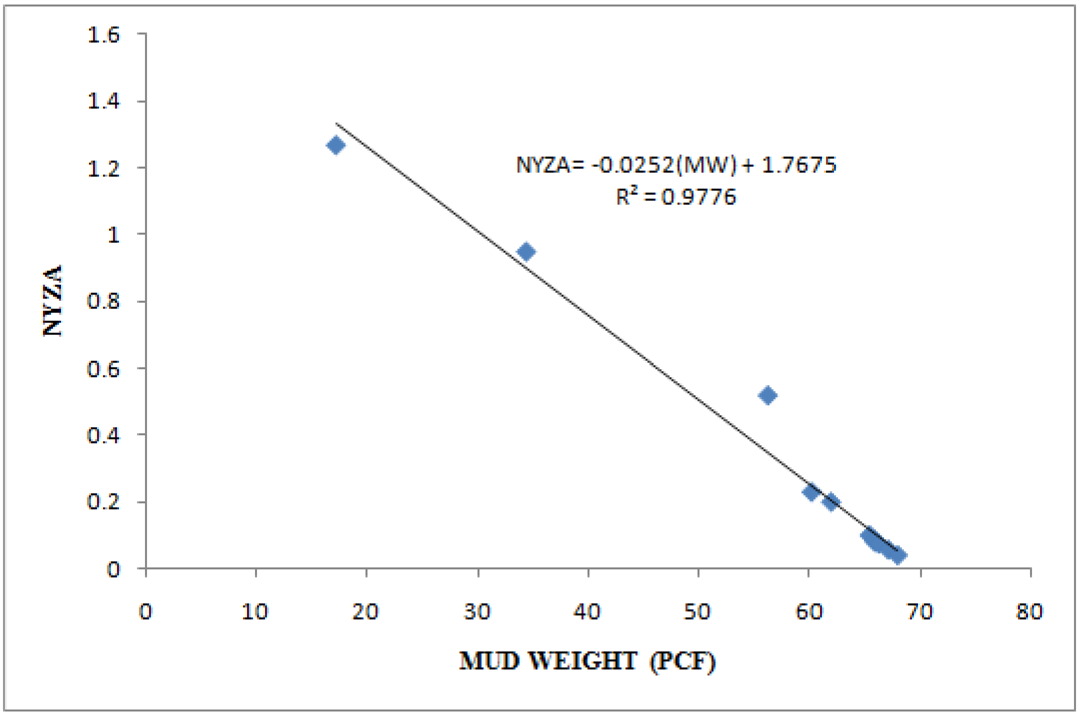


Figure 6 The relationship between NYZA and mud weight.

Conclusions

1) If the equivalent stress is less than yield stress (N is less than 1), the material will be in elastic mode; if the stress ratio (N) is equal to or greater than 1, the material is in the yield mode.
2) Mud weight equal to 68.4 PCF is the optimal mud weight for the studied well.
3) The results obtained from FEM are more accurate than of FDM.
4) The relationship between the NYZA and the mud weight is a linear relationship.

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