IMPROVED WELLBORE STABILITY PREDICTION BY APPLICATION OF SWELLING PRESSURE

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ABSTRACT

Optimization of drilling fluid parameters such as mud weight and salinity is essential to mitigate instability problems during drilling shale sections [1]. No doubt the rock-drilling fluid compatibility is most important for maintaining wellbore stability but even the best mud chemistry will not assure stability in case of unfavorable combination of rock and stress parameters and at least some of wellbore instability cases can be explained on the ground of rock mechanics.

This paper presents results of mathematical model which allows prediction whether the well will be stable or not in intervals with known rocks compressive strength, Poisson's ratio, depth of deposition and mud density. It is possible to calculate the minimum and maximum mud density required to maintain wellbore stability in intervals deposited at the given depth, fracturing pressure, allowable surge and swab pressure, maximum allowable drawn down pressure which must not be exceeded during production.

Chemical aspects of interaction shale-drilling fluid has been introduced to the model by taking into account swelling pressure of clay minerals which was determined using standard laboratory methods and estimations using diffuse double layer (DDL) theory [2-4]. Furthermore, correlation of swelling pressure/swelling (increase of volume) versus petrophysical parameters, mechanical data and mineralogical composition determined using X-ray Diffraction (XRD), Fourier Transformed Infrared Spectroscopy-Attenuated Total Reflection (FTIR-ATR) and Scanning Electron Microscopy (SEM) was found.

On the basis of measured and calculated values of the swelling pressure it was possible to estimate the minimum and maximum density of mud (only one mud parameter we can control to maintain stability of the well).

INTRODUCTION

Crushing of rocks at the wellbore wall accompanied by plugging the well by crushed material and partial or total loss of circulation are colloquially named "wellbore instability". The silty rocks – mainly shales – are the most complex rocks which constitute 75 percent of all rocks encountered while drilling and are blamed for 90 percent of all drilling problems such as wellbore instability, hole enlargement, heaving shales, bit balling, loss of circulation, pipe sticking, side tracking and the like [1].

Shales are low permeability, sedimentary rocks that have distinct laminated layers and moderated to high clay content. Those features makes them susceptible to phenomena such as hydration, swelling, shrinking, strength reduction and ultimately failure. The mechanisms controlling these phenomena are very complex and not fully understood.

Many researchers argue that these phenomena are attributed to water and ion transfer into shales which alter the mechanical and physicochemical properties of shales and could lead to wellbore instability problems during drilling.

The vast majority of these problems are believed to be caused by improper compatibility of drilling mud resulting in chemical reactions at the mud and rock interface and causing clay swelling plus loss of well integrity. While we share the above opinion we believe that at least some of the wellbore instability cases can be explained on the ground of rock mechanics, assuming state of stress at the wellbore wall depicted in [5]. Wellbore instability may be caused by exceeding of allowable material effort at the wellbore wall, restriction of wellbore drift diameter which is caused by side forces (elastic and plastic deformations in salts and plastic shale caused by overburden loads) and loss of stability of a circular cross section of a well.

In Oil and Gas Institute-National Research Institute the mathematical model has been developed which allows to predict whether the well will be stable or not in intervals with known rocks compressive strength, Poisson's ratio, depth of deposition and mud density. This model allows for computation minimum and maximum mud density required to maintain wellbore stability in intervals deposited at the given depth, fracturing pressure, allowable surge and swab pressure, maximum allowable drawn down pressure which must not be exceeded during production. Moreover, taking into consideration physico-chemical reactions, it is possible to determinate safe mud weight limits which take into account the shale swelling pressure.

The basis of the mathematical model

Before the well is drilled the rock mass is under certain three dimensional state of stress. Each rock element at any depth is compressed by principal vertical pressure caused by weight of overburden rocks and two principal horizontal pressures. During drilling, the state of stress around the borehole is changed, since the rocks lost the side support provided by removed material. We assume that the rock behaves as elastic material and that destruction of rock at borehole wall takes place when stress concentration exceeds the allowable limit of material effort, which is defined here using the maximum principal strain hypothesis which holds for brittle materials such as rocks.

The vertical pressure p_z exerted upon any layer deposited at depth z is caused by weight of overburden rocks (with average specific gravity γ_s) and equals to:

$$p_z = \gamma_s z \tag{1}$$

It is commonly believed that vertical (or overburden) pressure is opposed both by rock matrix and pore pressure p_0 and thus the effective vertical pressure $\overline{p}_z$ acting on rock matrix is:

$$\overline{p}_z = p_z - p_0 \tag{2}$$

We assume that vertical pressure is additionally opposed by swelling pressure of clay minerals caused by water based mud filtrate invasion into clay double layer. Shales tend to increase its volume which is caused by water absorption of clay minerals in wellbore zone. Because shale cannot freely increase its volume in this zone this leads to decrease of pore space and additional increase of pore pressure by the value of swelling pressure p_p. There is no pressure transmission between shale and mud because of the extremely low permeability of shale and relatively large porosity. In this case we need to modify Equation (2):

$$\overline{p}_z = p_z - \left(p_0 + p_p\right) \tag{3}$$

The effective radial pressure $\overline{p}_r$ at the borehole wall equals to the sum of radial pressure caused by tendency of material subjected to compression for side expansion towards the hollow space (well), pore pressure p_0 and swelling pressure p_p (which are acting in all directions) minus the hydrostatic pressure of drilling mud p_m, which counteracts pressures mentioned above. Thus, the effective radial pressure may be expressed as:

$$\overline{p}_r = \frac{\mu}{1-\mu}\overline{p}_z + p_0 + p_p - p_m \tag{4}$$

where μ is Poisson's ratio. Knowing the pressure (stress) values at the borehole wall one can calculate the material effort using the maximum principal strain hypothesis (or other ones) and tell whether stress concentration exceeds the allowable limit.

Mathematical model and derivation of basic formulas is described in details in [5]. Presented equations allow for calculation of values specified below, provided that shale strength properties such as Poisson's ratio μ and unconfined compressive strength R_c as well as the average density of overburden rocks γ_s, actual mud density and pore pressure gradient α are known. The mud compatibility, which is believed to be the most important factor influencing wellbore stability in shale, has been introduced to the model by taking into account swelling pressure of clay minerals:

a) critical depth (z_{crit}) which is a maximum depth at which shale of known strength properties maintains its integrity for constant overburden pressure gradient, pore pressure gradient, swelling pressure and mud density

$$z_{crit} = \frac{-\frac{\mu}{1+\mu}R_c}{\gamma_s \frac{2\mu^2}{1-\mu^2} + \alpha\frac{1-3\mu^2}{1-\mu^2} - \gamma_p} \tag{6}$$

b) minimum mud weight $\gamma_{m\min}$ required to maintain wellbore stability in shales of known strength properties deposited at actual depth z,

$$\gamma_{m\min} = \gamma_s \frac{2\mu^2}{1-\mu^2} + \alpha\frac{1-3\mu^2}{1-\mu^2} + \frac{R_c}{z}\frac{\mu}{1+\mu} \tag{7}$$

c) maximum mud density $\gamma_{m\max}$ for which shale with known strength properties preserves its integrity at the wellbore wall for any depth assuming that the overburden pressure gradient and pore pressure gradient are constant.

$$\gamma_{m\max} = \gamma_s \frac{2\mu^2}{1-\mu^2} + \alpha\frac{1-3\mu^2}{1-\mu^2} \tag{8}$$

In Eq. (6) – (8) $\alpha = (p_0 + p_p)/z$ is pore pressure gradient.

In practice the mud weight is only the factor we can use to maintain the wellbore walls stability.

Model presented in [5] may also be used to provide formulas for fracturing pressure (and fracture gradient), which is a well-known Hubbert, Willis formula.

$$p_{frac} = z\left[\frac{\mu}{1-\mu}(\gamma_s - \alpha) + \alpha\right] \tag{9}$$

Swelling pressure, which is incorporated to the model in Eq.3, can be measured or calculated. Based on the diffuse double layer (DDL) theory for interacting particles following equation were used to compute swelling pressure for clays[2,6]:

$$p = 2n_0 kT(\cosh u - 1) \tag{10}$$

where p is the swelling pressure (N/mm^2), n_0 is the ionic concentration of the bulk fluid ($ions/m^3$), u is nondimensional midplane potential, k is the Boltzmann's constant (J/K), T is absolute temperature (K). Determination of swelling pressure requires nondimentional midplane potential function and therefore extended knowledge about the rock properties like cation exchange capacity, specific surface area, porosity, valency of exchangeable cations, void ratio of the clay specimen etc.

MATERIALS & METHODS

Samples

In order to verify the model several samples were chosen from cretaceous with early diagenesis, poor compaction and high content of kaolinite, strong diagenesis, metamorphic carboniferous mudrocks and Silurian and ordovician samples which reveals carbonaceous composition, with the bulk of quartz an clay minerals. Mineral composition strongly affect geomechanical parameters of the samples what is shown in Table 1 and Figure 1.

Methods

For all samples uniaxial geomechanical measurements in order to determine unconfined compressive strength, Poisson's ratio and Young modulus were performed. To incorporate to the model swelling pressure laboratory tests on compacted shale samples were carried out under isochoric conditions using high pressure constant volume cell. During the swelling pressure test distilled water was supplied from burette via the top inlet of the cell. The full saturation of tested specimen was confirmed by the time-swelling pressure response.

In order to calculate swelling pressure using diffuse double layer (DDL) theory several parameters like porosity, density, surface area, cation exchange capacity, mineral composition were measured.

Dynamic porosity and surface area was calculated from the measurement performed on porosimeter AutoPore IV mercury as well as nitrogen isotherm adsorption method. Cation exchange capacity (CEC) which is one of the most important properties of clays in terms of their performance was measured using cobalt (III) hexamine method. Moreover, to verify mineral composition of the samples the FTIR method was applied, and the results were correlated with X-ray diffraction measurements and SEM mineral mapping.

RESULTS & DISCUSSION

Many researchers have attempted to use the Gouy-Chapman diffuse double layer theory for determining the swelling pressure of clays. Earlier studies have pointed out some

differences between experimental data and relationships derived theoretically from the diffuse double layer theory, which may be attributed to: poorly or partially developed double layer, surface hydration forces at close particle distance, non-uniform size of clay plates, existence of electrical attractive forces, presence of multivalent cations, effect of ion size, anion adsorption, partical size etc. One of these factors or the combination of several above mention factors may contribute to the difference between the theoretical and experimental results depending on the initial stress state of clay [2,4]. In the case of Silurian shales to which calculation of swelling pressure from DDL theory was possible experimental data are in very good agreement with estimated one (Figure 2).
In the case of unconsolidated rocks with high content of kaolinite swelling pressure have a great impact on wellbore stability. Calculated from the model critical depth and mud weight limits which incorporate swelling pressure differ in those parameters of over 1500 m and 250 kg/m^3, respectively. Also in the case of Silurian shale, which have generally very poor reactivity, the biggest discrepancy was observed for the samples with the lowest quartz content (sample 5, 6 and 9) what indicate influence of clay minerals on wellbore stability.

CONCLUSION

It is difficult to indicate the single reason for loss of well integrity in shale interval since there are many factors which influence the shale behavior – the mud compatibility being the most important. As mentioned before the problem of well integrity in shales is extensively discussed in technical literature. We believe that apart mud chemistry and interactions with shale, there are situations when loss of shale integrity should be considered on the ground of rock mechanics. There are many models presented and numerous papers dealing with well stability problems in shale but they share two common features: they are complicated and difficult to use in practice. The model presented herein, being quite simple, is easily applicable and the conclusions are reasonable.

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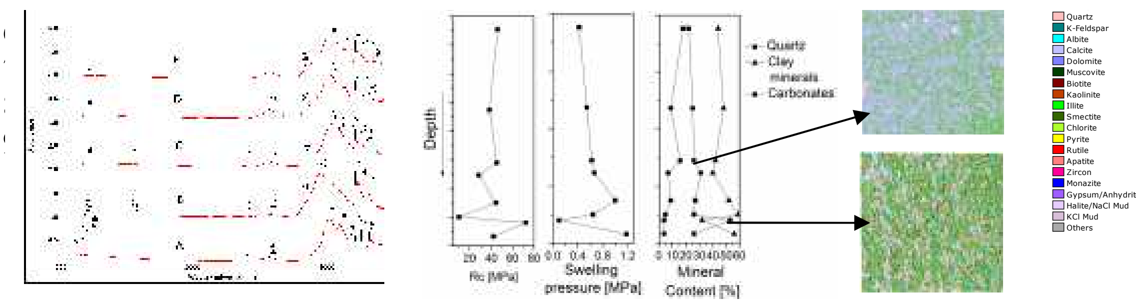
Table 1 results from CEC and geomechanical measurements reveal differences in mineral composition of selected samples

Sample number	Stratigraphy	Swelling pressure	Unconfined compressive strength	Poisson's ratio	Young modulus	CEC
		[MPa]	[MPa]	[-]	[GPa]	[meq/100g]
1	Cretaceous	4.70	9.94	0.26	1.049	-
2	Carboniferous	0.08	35.08	0.08	5.244	-
3	Carboniferous	0.05	70.90	0.09	9.914	-
4	Carboniferous	0.06	56.37	0.14	6.739	-
5	Silurian Ludlow	0.42	45.87	0.16	7.263	9.6
6	Silurian Ludlow	0.54	45.12	0.18	9.507	6.55
7	Silurian Wenlock	0.66	38.30	0.33	3.606	7.62
8	Silurian Wenlock	0.62	28.16	0.31	2.420	7.95
9	Silurian Llandovery	1.00	44.20	0.02	8.610	6.61
10	Silurian Llandovery	0.64	10.19	0.06	1.233	12.88
11	Ordovician	0.10	72.18	0.14	6.795	11.57
12	Ordovician	1.18	42.08	0.14	7.670	8.13



a) b) c)

Figure 1 Correlative a) FTIR (A-1, B-11, C-10, D-9, E-7) b) XRD c) SEM mineral mapping analysis reveals the bulk mineralogy of the specimen

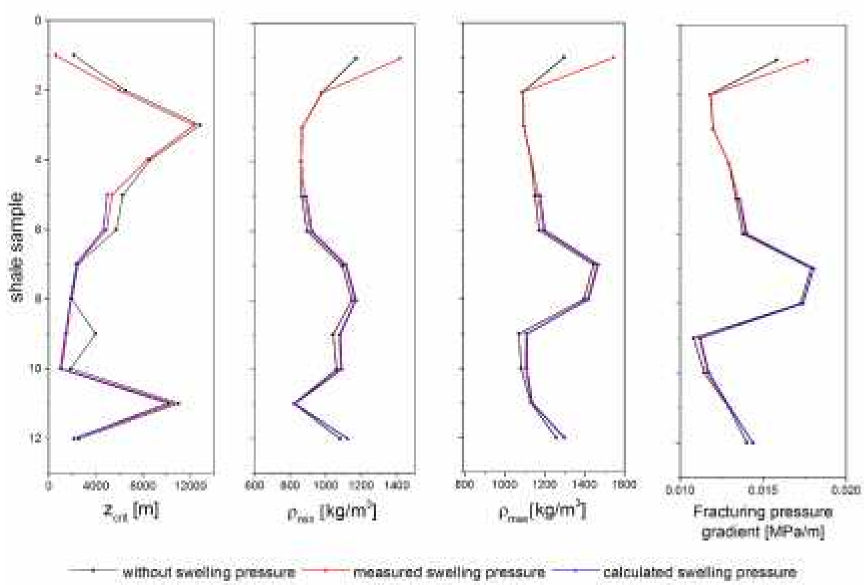


Figure 2 Result of computation of critical depth and mud weight limits (min – max) for model without swelling pressure (black curve), with measured swelling pressure (red curve), with calculated from DDL theory (blue curve)