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AN OVERVIEW OF OIL WELL DRILLING PROBLEMS IN SHALE FORMATIONS

(Case Study: Asmari Reservoir)

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Abstract: Shale layers are found in 75% of the drilled sections in Iran, which causes 90% of the problems of instability of wells, and this can cause a number of problems, such as complete or partial collapse of the well or even loss of the well before it reaches its goal. On the other hand, the costs of instability can be reduced when drilling in shale formation using analytical and numerical methods considering the correct parameters. With the right understanding, we can help stabilize it. Preventing the problems caused by shale formations and resolving these problems requires an understanding of the features of the formation, familiarity with the changes caused by the physical and chemical interactions of the fluid, and awarness of the physiochemical properties of the drilling mud.

Keywords: *Oil wells, Drilling, Shale Formations*

1. Introduction

One of the major problems in drilling and exploration is the existence of deep-seated shale layers during drilling to production oil and gas. Despite extensive studies on the shale layers and their complex properties, the problems of shale layers still raise the cost of drilling oil wells. Most of the research on shale has investigated the physical and chemical properties of its behavior during and after drilling, attempting to stabilize the shale by introducing relationships for changes in drilling mud compounds. The study of shale from the perspective of rock mechanics is a new aspect of the studies that is being developed in recent years. One of the important issues in studying the stability of horizontal wells is the determination of in situ stresses. According to research, rock strength is a more important factor in rock stability than other parameters such as elastic properties of rock, drainage conditions, and layering surfaces [4, 19]. Shales containing clay minerals can react with aqueous base drilling mud and the inflation created by this reaction causes instability. In addition, shale rocks are weakly cemented and hardened at genesis and they are washed and eroded by the flow of mud. Another factor in the high tendency of shales to be unstable is their very high pressure.

Because the shales have very low permeability in the picodarcy to microdarcy range, and often because of the high initial deposition rate, the shales have much higher pressure than other sediments. Due to the low permeability of the shale, the mud cake does not form effectively in the well wall, so the formation does not have a good shield against well hydraulic pressure. On the other hand, induced hydraulic pressures due to low permeability are not able to diffuse rapidly within the formation to reduce effective stresses. Taken together, these factors increase the instability of the well. Drilling in the Iranian reservoirs where the shale layers are found is no exception and there are many problems for drilling companies. Asmari reservoir, one of the largest oil reservoirs in Iran, has shale layers and in this paper we will discuss its shale formations, look at shale types and their instability as investigated in theory and then take a critical look at the research that has been done on this field.

Studies by numerical methods can be attributed to the work of Low and Anderson in 1958 where, for the first time, using the thermodynamic relationships between water movement and ion exchange, they were able to propose a relationship called the osmotic pressure relationship. According to their research, to stabilize the well wall, a fluid with the lowest activity should be used, thereby reducing the osmotic pressure, which in turn would lead to stability and lowering the inflation of the shale wall [12]. Mohammadzade Sani investigated the stability of the well wall in the shale formation by FLAC3D software [16]. Mengjiao et al. investigated the model of wall instability in shale formations [14], which included parameters such as pro-elastic and chemical effects [3].

2. MINERALOGY OF CLAYS

Clay is a generic term that used to describe sediments, soils and very fine rocks. It is asoil material that aggregate one or more clay minerals with possible tinctures of quartz (SiO_2), metal oxides (Al_2O_3, MgO, etc.) and organic matter.Geologic clay deposits are mostly composed of phyllosilicate minerals containing variable amounts of water trapped in the mineral structure. Clays are plastic due to particle size and geometry as well as water content, and become hard, brittle and non-plastic upon drying.

This clay feature is due to the presence of some clay minerals in their structure. Clay minerals are fine-grained aluminosilicate minerals with microscopic structure. In the mineralogical classification, clay minerals fall into the group of sheet silicate minerals, because their main structure is layered and made of aluminum and silicate sheets. Each layer is like a thin sheet that it is called the single layer. Examples of sheet silicate minerals are mica and vermiculites, which are divided into thinner layers along their cleavage. Depending on the type of repeating plates in the mineral structure, clay minerals can also be divided by the number of silicate to aluminum plates, such as 1 : 1, 1 : 2, 2 : 2, etc. Clay is also called a batch of particles less than 2 microns in diameter that contains most of the clay minerals [23].

Most excavated clays have the same composition, structure and are derived from the weathering of igneous minerals. They later became sedimentary rocks due to their transport and compaction. Each clay network consists of two tetrahedral silicon plates and one central aluminum octahedral plate. The corners of the tetrahedral plate are located toward the center of the network and form one layer with one of the octahedral hydroxyls. These two panels are horizontal, continuous and separated in the Z direction. The O^{-2} layers of each tetrahedral are adjacent to each other and between them there is a weak link and a Well-formed cleavage panel. Between these networks is water formation, so that both hydrogen atoms are opposite an oxygen layer [23]. The difference between the different clay minerals is in the deposition of aluminum in the central octahedral layer and the silicon in the tetrahedral layers, as well as the location of the other cations. This combination causes electrical instability, which is compensated by the absorption of cation into the intercrystalline region [21]. Diagenesis of clay minerals occurs in the following order:

- feldspar (mother minerals, weathered)
- smectite
- mixed-layer clays (periodically smectite and illite)
- illite and muscovite.

The conversion of clay minerals from each step to the next is accelerated by catalysts such as burial depth and geothermal heat. In this cycle, the activity for water absorption and cation exchange is gradually reduced [19]. Hydration and dispersion are two major mechanisms when reacting water with clay and shale formations. This reduces the compressive strength of these rocks [24].

3. Calculation method of vertical, minimum horizontal and maximum horizontal stresses of the shale layer of the Asmari Formation

Using log well data, it can be found that the shale layer occurs from the depths of 3,915 to 3,930 meters and because of the high shale gauge ratio (SGR) value at a depth of 3,915 m and the shale being pure, this depth has been chosen as the basis for the horizontal section studied to obtain vertical, minimum horizontal, and maximum horizontal stresses. The vertical stress is calculated by [25]

$$a_v = y \times h \, , \tag{1}$$

Where *y* is the average density of rocks from the surface of the earth to a depth of 3,915 meters in g/cm^3, and *h* is the given height in meters (depth 3,915 m). According to the average lithological density of the well, the vertical stress *vs* at the depth of 3,915 m was 98.17 MPa. To obtain the minimum and maximum horizontal stresses ($S_{H\,min}$ and $S_{H\,max}$), Anderson's fault theory is used to determine the stress regime. The values of the minimum and maximum horizontal stresses can be calculated using *Equations (1)* and *(2)* for different fault conditions [25].

Table 1

Relationships used to obtain mechanical and resistive properties of shale

Parameters in the equations	Equations
V_p is the longitudinal wave speed in meters per second and ΔT_p is the time of passing the wave length. [6]	$V_p = \frac{1}{\Delta T_P}$
σ_c is uniaxial compressive strength in MPa and V_p is the longitudinal wave velocity in kilometers per second.	$\sigma_c = 0.77V_p^{2.93}$
$\emptyset$ is the angle of internal friction in degrees, and v_p is the longitudinal wave velocity in meters per second. [25]	$\Phi = sin^{-1}(\frac{V_p - 100}{V_p + 100})$
C is adhesion. S_0 is uniaxial compressive strength. μi is the angle tangent of internal friction. [25]	$2C = S_0[(\mu_i^2 + 1)^{\frac{1}{2}} \_ \mu_i$
v_c is the transverse wave velocity v_p is the longitudinal wave velocity in meters per second. [15]	$\frac{V_p}{V_s} = 1.89$
ΔTS is the transverse wavefront in second per meters and the transverse wave speed is in meters per second. [6]	$\Delta T_s = \frac{1}{V_s}$
Ed is a dynamic elastic modulus in MPa, ρ is the density in kilograms per cubic meter, v_p is the longitudinal wave velocity in meters per second and v_s is the transverse wave velocity in meters per second. [17]	$E_d = \rho V_S^2 \frac{(3V_P^2 - 4V_S^2)}{(V_P^2 - V_S^2)}$
ν is the Poisson's coefficient, v_p is the longitudinal wave velocity in meters per second and v_s is the transverse wave velocity in meters per second. [17]	$v = \frac{V_P^2 - 2V_S^2}{2(V_P^2 - V_S^2)}$
ES is a static elastic modulus in GPa and v_p is the longitudinal wave velocity in meters per second. [10]	$E_s = 0.076V_P^{3.23}$
G is the shear modulus, E is a static elastic modulus and V is Poisson's coefficient. [25]	$G = \frac{E}{2(1 - v)}$
K is the modulus of the bulk, E is a static elastic modulus and V is Poisson's coefficient. [25]	$K = \frac{E}{3(1 - 2v)}$

Normal faulting
$$\frac{\sigma_1}{\sigma_3} = \frac{S_v - P_p}{S_{H_{min}} - P_p} \leq [(\mu^2 + 1)^{\frac{1}{2}} + \mu]^2 \quad (2)$$

Reverse faulting
$$\frac{\sigma_1}{\sigma_3} = \frac{S_{H_{max}} - P_p}{S_v - P_p} \leq [(\mu^2 + 1)^{\frac{1}{2}} + \mu]^2 \quad (3)$$

Where σ_1 is the principal maximum stress, σ_3 is the principal minimum stress, SV is vertical stress, $S_{H\,max}$ is the maximum horizontal stress, $S_{H\,min}$ is the minimum horizontal stress, P_P is the pore pressure of the formation and μ is the angle of internal friction. By placing a value of 34.4 MPa for the pore pressure at high relationships, the value of $S_{H\,max}$ is 301.2 MPa and the value of $S_{H\,min}$ is 49.5 MPa (according to unpublished documents from the South Oil Company).

Assuming $S_{H\,max}$ as the vertical line and $S_{H\,min}$ as the horizontal line, the stress polygon can be plotted for the desired depth. This polygon defines the possible values of minimum and maximum principal stresses at any depth based on Anderson's fault theory as well as Moore-Coulomb's fault theory with a friction coefficient and pore pressure [1]. This polygon of the stress is plotted in *Figure 1*.

The optimal weight of the drilling mud can be determined by calculating the amount of collapse pressure and fracture pressure according to the stress conditions in a vertical well. If the calculated values of the collapse pressure (P_{Wf}) are greater than the actual mud pressure value in the well, the well will fail. Likewise, if the calculated values of failure pressure (P_{Wf}) are less than the actual value of mud pressure, the well will fail and it will be disrupted [2].

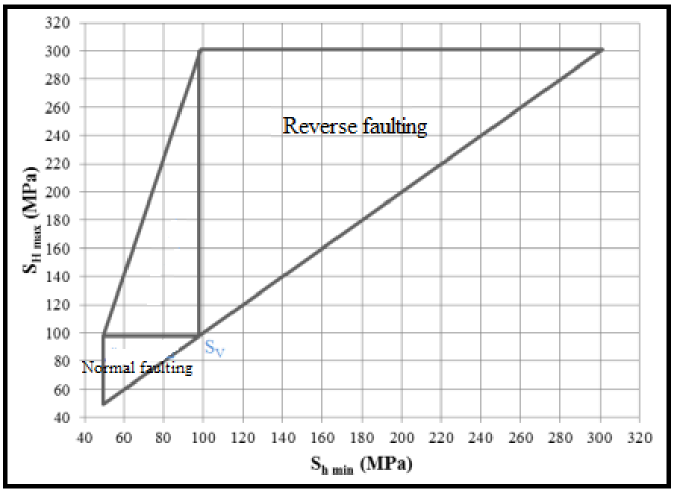

Figure 1

Stress Polygon for a depth of 3,915 meters and a pore pressure of 34.4 MPa

4. ADVANTAGES AND DISADVANTAGES OF OIL SHALE

Oil shales are distributed around the world and most of them are in the United States. By 2007, Brazil, Estonia and China were extracting oil shale. Geological surveys were carried out in Iran in the southern Alborz region in 1955 and in Ghalikoh and Zardkoh Lorestan in the year 1979, according to the Exploration Management Announcement. Experiments with oil shale in the region have shown that the grade of the oil exceeds the world average. However, due to the impoverished areas and high costs of production, extraction and production of these resources is not currently a priority. In terms of estimating the volume of these reserves, according to an initial estimate made by the American company TOSCO in 1955, a significant amount of available reserves has been announced. Projects are currently being developed to estimate the volume of these reserves in the National Petroleum Exploration Management [5].

5. KEY PARAMETERS OF GAS SHALE EVALUATION

Among the parameters used to evaluate the gas shale, the following can be mentioned: Total Organic Carbon (TOC) (wt%): Its value can be estimated using different well logs or through laboratory analysis.

Maturity: Maturity is one of the important parameters for evaluating oil shales, which can be investigated through geochemical and mapping data. As can be seen in *Figure 2*, in immature rock (Ro < –0.5) the gamma diagram has a high irregularity, whereas in adult rock (Ro = 1) this irregularity is very low. Also, the separation rate (ΔlogR) of the resistivity and sonic diagram is high in adult rock and therefore will show more TOC. However, these two diagrams in the immature rock are completely irregular and show little separation. Geochemical parameters such as vitrinite reflectance coefficient, maturity index biomarkers and maturity-related carbon isotopes can be mentioned [20].

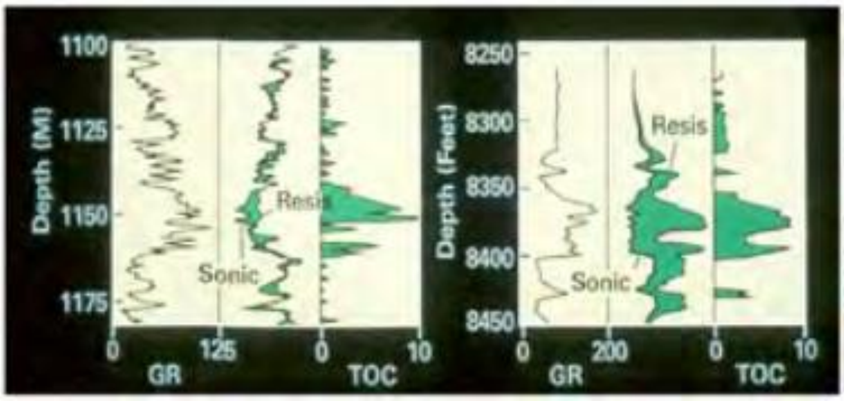

Figure 2
Diagrams used in maturity study (left in immature rock & right in mature rock)

Geochemical parameters (hydrocarbon type and quality): The type of kerogen can be determined using hydrogen index versus oxygen index (HI/OI) graphs or the atomic ratio of oxygen to hydrogen. T_{max} and other parameters can also be used for other evaluations such as maturity.

Total porosity: It can be used to evaluate porosity using a rock sample crushing method and also based on neutron, sonic and density diagram data.

6. Ways to Deal with Instability When Drilling in Shale Layers

One of the major problems in drilling and production is the existence of deep-sea shale layers during drilling for oil and gas extraction. Despite many studies on shales and their complex properties, problems caused by the presence of shale layers still raise the cost of drilling oil wells. Most of the research on shale has investigated the physical and chemical properties of its behavior during and after drilling and has attempted to make the shale drilling mud composition more stable by introducing relationships [4, 18]. Chemical instability is often found in shale formations and is strongly influenced by drilling fluid composition. Shale is the most complex rock and is not well understood to this day. Shale properties include low porosity and permeability due to the large amount of clay minerals. Chemical reaction with aqueous base drilling fluids may cause serious problems in the stability of the well wall. Finally, the most effective way to solve or manage problems caused by shale instability may be weight, type, chemistry and particles of drilling mud, as well as the strategy of drilling a wall pipe [22]. Investigating shale from a rock mechanics perspective is a new aspect of the studies that has been under development in recent years. Determination of horizontal stresses is one of the important issues in the study of stability of horizontal wells. Changes in pore pressure have a significant effect on well stability during shale drilling, ecause shale has low permeability, as mentioned, and the flow of ions and water in it is very slow. It is argued that during drilling, there is a major pressure change near the well wall and there will be a large inductive pore pressure gradient in that small area.

7. Investigation of Drilling Problems in Cracked Shale Layers of Dashtak Formation

Problems in the drilling industry include dealing with shale formations and controlling the instability and loss of wells in these layers. In recent years we are witnessing continuous research in the study and production of new mud and polymer materials in the mud industry. All of these moves are aimed at finding a viable, low-cost solution to hydrocarbon resources. One of the most important problems in drilling wells in the Fars region used to reach the huge gas reserves in the Ofogh-e-Dahrom is crossing the shale Dashtak Formation. There are several drilling problems associated with one of the thickest and most important formations of Iran, which in the gas reservoirs of Ofogh-e-Dahrom acts as an excellent rock cover. The numerous mud waste in this formation have causes many problems in drilling wells in this region. Thus, drilling professionals are always been looking for solutions to overcome these problems.

The presence of waste and falling of the well wall not only increases the cost of drilling due to the high cost of materials used in mud, but also causes other major problems such as the instability of the well and the clogging of drilling pipes. Also, the residue left in the well due to the shale loss should not be ignored. Residual operations also require a great deal of time and expense in drilling operations. Residual operations in the shale formation are more difficult than in calcareous formations due to the waste and loss of the shales. Therefore, detailed studies should be carried out on drilling in this formation or in shale layers in general [13].

Shale layers of the Borgan Formation

Identification and detection of clay minerals begins with sampling. Depending on the type and number of experiments, the core and shale sediments of the formation are sampled. It is advisable to specify the exact location of the sample for each of the experiments in the area map. The Borgan Formation of the Cretaceous is one of the most important rocks of the Persian Gulf hydrocarbon reservoirs. The Borgan Formation is an oil field consisting of fine-grained to medium-grained sandstones, rock clay, calcareous shales and carbonate-limited sequences [7, 9]. According to the type of experiments, the required number and amount of shale cores from the Borgan Formation at depths of 2,208 to 2,254 m wells were sampled by the employer. Experiments and identification methods were determined and implemented using the laboratory experiences of colleagues at the Petroleum Industry Research Institute as well as the results of studies in related published articles [11]. These samples will be used for experiments to study and identify clay minerals among shale layers including X-ray diffraction (XRD) analysis, scanning electron microscopy (SEM), X-ray fluorescence (XRF) and more. In this experiment, based on the results of different experiments on samples of core wells, it can be stated that the major minerals of shale formations samples are quartz and clay minerals. Kaolinite, with a frequency of 66%, and illite, with a frequency of less than 12%, are the most abundant clay minerals in the samples and quartz is the most abundant mineral, up to 32%. The size of the quartz particles is mainly in the range of silt to fine sand.

8. INVESTIGATION OF DRILLING PROBLEM OF SHALE AND MARNI FORMATIONS

Habibnia and Dinarvand [8] studied the Maron oilfield, one of the most important fields in the Zagros oil basin (40 km east of Ahvaz). From the geological point of view, the field is located in the northern of Dezful and between the Koopal, Aghajari, Ramin, Shadegan and Ramshir fields, as shown in *Figure 3*. According to [8], 320 wells had been drilled in the field up to that point (2012 or 2013). The extensive presence of shale sediments along with high amounts of marn in the stratigraphic column has caused many problems during the drilling of wells in this field. Therefore, conducting this study in this field is essential and can provide valuable results for tackling the problems of tube entrainment. In their study, 18 shale samples and more than 30 marn samples from 8 wells with different depth intervals were tested. Since most shale minerals are composed of silicates, hydrofluoric acid (HF) was used as one of the main materials of the designed fluid. First, the powdered sample was sifted uniformly and placed in a pill making machine. The tablets were pressurized and prepared by applying a force of 60 kN. The pills were carefully weighed and then placed in different solvents. After 20 minutes, these pills were weighed again. The results are presented in *Table 2*. The observed weight difference indicates the degree of disintegration [8].

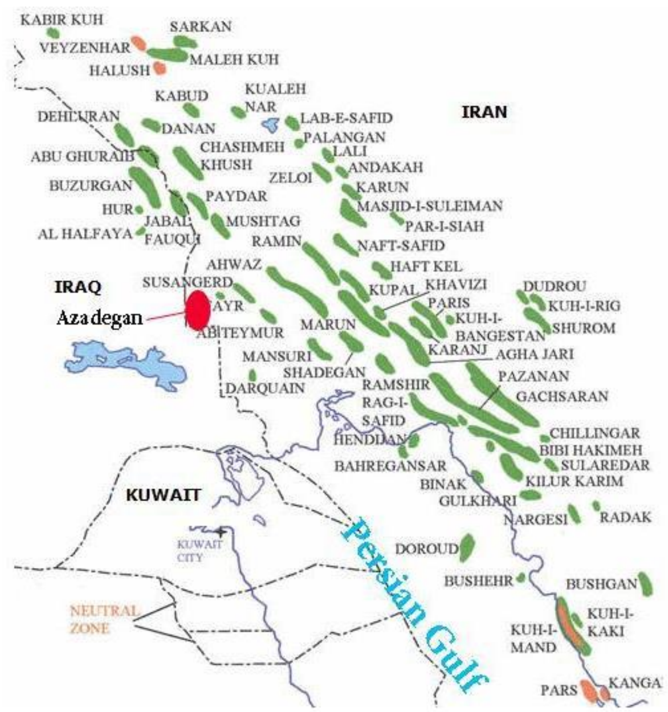

Figure 3
The position of the Maron oilfield and its adjacent fields

Table 2
Results of using different solvents with one type of pills

Original material	Solvent	Time to minute	Result
HF2%	Urban water	20	Inflation
HF5%	Urban water	20	There was not much difference, but the appearance of the pill became more fragile and corrupted
HF5%	Water saturated with NaCl to prevent shale inflation	20	1 – Reduce the corrosive power of acid. 2 – Weight difference was negative due to NaCl deposition 3 – No shale Inflation
HF5%	Alcohol	In less than a few minutes, the pill was completely destroyed	High disintegration and low inflation

Original material	Solvent	Time to minute	Result
HF2%	Alcohol	In less than a few minutes, the pill was completely destroyed	High disintegration power and low inflation (best result)

Achieving meaningful results without affecting the shape and size of drill cutting requires uniform grading and the conditions used in various experiments. That is why all the samples used in the experiment were prepared by first grinding mill and then in the form of pills of equal size, done by a special template designed by the researchers. Using the results obtained from the experiments performed, the best combination of the quenching fluid and its properties were found to be:

- HF acid as the main dispersant of shale;
- HCl acid to dissolve impurities and create a contact area for the main acid;
- Alcohol as an accelerator of action [8].

9. CONCLUSION

Well instability in drilling operations can be due to formation leaching, erosion of the well. Of all the formations that exhibit extreme instability, shales have been identified as the most problematic in that 90% of the problems of instability of wells are related to drilling in shale layers. According to the well log data studied, Anderson's fault relationships, using the Mogi-Coulomb fracture criterion reveal that the stress regime is normal in the studied well range. Optimization of mud weight is essential to reduce well fall and problems associated with related to it and to reduce drilling mud invasion into the formation. To stabilize the well wall, the mud pressure must be selected that is between the collapse pressure and the fracture pressure.

Due to low porosity and permeability, low efficiency and the high cost of oil and gas shale, countries with less conventional resources pay less attention to this source. However, in recent decades, in the United States, due to the rise in fossil fuel prices, oil shale has been exploited. Harvesting from shale sources is dependent on fuel prices and technology availability. The presence of nitrogenous and oxygenated compounds gives rise to specific properties such as gravity and specific odor in shale oil.

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