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Mechanical parameters of drilling as factors of operational detection of high-pressure zones

Parametry mechaniczne wiercenia jako czynniki operacyjnego wykrywania stref wysokiego ciśnienia

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ABSTRACT: The article analyzes methods and technologies for assessing abnormal reservoir pressure and operational detection of abnormally high pressure zones when drilling oil and gas wells. Prevention of accidents and complications by detecting these zones is assessed as one of the main methods to improve the efficiency of oil work. Methods for detecting abnormal reservoir pressure, as well as signs used for this purpose, are systematized and classified. The advantages of the developed methods, which are based on the dependencies between technical drilling parameters, are substantiated, since the systems created on their basis allow detection in real-time without stopping drilling. We conducted monitoring to identify the state of application of modern digital technologies in drilling and operating oil and gas wells in the Azerbaijani oil and gas company SOCAR (as part of the company's grant project). In particular, the situation with the assessment of abnormal reservoir pressure and the automation of the processes of forecasting zones of abnormally high reservoir pressure were determined. The main results of monitoring are noted. The feasibility of using modern digital technologies to predict zones of abnormally high reservoir pressure in the SOCAR company is substantiated. Some recommendations and proposals are given for this purpose. A method is proposed that is included in this group of operational detection, which also allows for the calculation of the density of the weighted drilling mud to counteract the abnormal pressure. A brief summary of the detection principle, functional blocks, and the operation of the system based on this method is given. An algorithm for the operation of the system has been developed. Based on this algorithm, a control program was written in the C++ programming language. The operability of the system was tested by laboratory experiments based on the method of computer simulation.

Key words: oil and gas work, well drilling, abnormally high reservoir pressure, accidents and complications, operational detection, operational detection method, operational detection systems.

STRESZCZENIE: Artykuł analizuje metody i technologie oceny nieprawidłowego ciśnienia w złożu oraz operacyjną detekcję stref o anormalnie wysokim ciśnieniu w czasie wiercenia otworów ropnych i gazowych. Zapobieganie wypadkom i komplikacjom poprzez wykrywanie tego typu stref oceniane jest jako jedna z głównych metod poprawy efektywności prac wiertniczych. Metody wykrywania nieprawidłowego ciśnienia w złożu, a także wykorzystywane do tego celu wskaźniki, zostały usystematyzowane i sklasyfikowane. Uzasadniono zalety opracowanych metod, które opierają się na zależnościach między technicznymi parametrami wiercenia, gdyż systemy opracowane na ich podstawie umożliwiają wykrywanie tego typu problemów w czasie rzeczywistym, bez zatrzymywania wiercenia. Przeprowadzono monitoring w celu określenia aktualnego poziomu stosowania nowoczesnych technologii cyfrowych w wierceniu i eksploatacji odwiertów naftowych i gazowych w azerskiej firmie naftowej i gazowej SOCAR (w ramach projektu grantowego firmy). W szczególności określono sytuację w zakresie oceny nieprawidłowego ciśnienia w złożu oraz sytuację automatyzacji procesów prognozowania stref o anormalnie wysokim ciśnieniu w złożu. Zwrócono uwagę na główne wyniki monitoringu. Uzasadniono celowość stosowania nowoczesnych technologii cyfrowych do prognozowania stref anormalnie wysokiego ciśnienia w złożach w firmie SOCAR. Przedstawiono niektóre rekomendacje i propozycje w tym zakresie. Zaproponowano metodę, która należy do grupy detekcji operacyjnej, pozwalającą również na obliczenie gęstości dociążonej płuczki wiertniczej w celu przeciwdziałania nieprawidłowemu ciśnieniu. Przedstawiono krótkie podsumowanie zasady wykrywania, modułów funkcjonalnych oraz sposobu działania systemu opartego na tej metodzie. Opracowano algorytm działania systemu. W oparciu o ten algorytm opracowano program sterujący w języku programowania C++. Sprawność systemu została przetestowana poprzez eksperymenty laboratoryjne przeprowadzone w oparciu o metodę symulacji komputerowej.

Słowa kluczowe: prace związane z ropą i gazem, wiercenie odwiertów, anormalnie wysokie ciśnienie w złożu, wypadki i komplikacje, detekcja operacyjna, metoda detekcji operacyjnej, systemy detekcji operacyjnej.

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Introduction

Macroeconomic indicators of many countries depend significantly on the oil and gas industry. The effectiveness of work in this area is primarily related to the level of development of techniques and technologies used in the processes of drilling, construction, and exploitation of wells. It is known that in the process of drilling and operation of any type of well, a number of accidents and complications (AC) occur due to abnormal reservoir pressure, which leads to a decrease in labor productivity. On the other hand, a number of serious accidents and complications can lead to significant losses of oil and gas, environmental pollution, and human casualties. Elimination of accidents and complications can lead to significant losses of time, human resources, and financial costs. In many cases, AC occurs as a result of abnormally high reservoir pressure (AHRP). Therefore, timely detection and operational detection of AHRP zones is considered one of the main ways to improve work efficiency. For this, advanced oil and gas companies use modern methods and technologies, systems created on the basis of detection methods. Studies show that for the purpose of detection of AHRP zones, systems created using the dependence between the mechanical parameters of drilling (MPD) are more widely used, taking into account a number of advantages.

World experience shows that zones of abnormally high pressure are found when drilling wells in all oil and gas-bearing provinces. This situation is especially typical for the geological conditions of the Baku Archipelago and the South Caspian Basin: it is explained, first of all, by the very complex geological and tectonic structure of the deposits, hydrodynamic conditions and the location of hydrocarbon resources in very deep layers of rocks (more than 6–7 km). (Dadashov and Abyshov, 2012; Suleymanov, 2022) On the other hand, it is necessary to annually increase the design depths of wells for the extraction of hydrocarbons. Such a situation increases the probability of encountering zones of abnormal pressure and makes the work on detecting these zones even more urgent. The obtained data show that one of the main reasons for the occurrence of AC when drilling wells is the presence of AHRP zones or zones of abnormally high pore pressure (AHPoP) in the drilled rock (Parisa, 2016; Mammadov et al., 2021).

Accidents and complications occur more often in countries (companies) that do not take advantage of modern advances in geological and geophysical sciences, modern techniques and technologies, including methods for detecting abnormal pressures, when drilling oil and gas wells, and these cases cause greater damage.

An example is the damage from a strong open gas fountain caused by AHRP high pressure during drilling of gas well No. 90 of the Bulla-Deniz field (horizon VIII, design depth 5800 m, Nadgyrmag Sandy Suite). The fountain lasted 68 days and caused daily losses: 8 million m^3 of gas condensate, 704 tons of oil, and seriously polluted the environment (Abdullayeva and Alizadeh, 2022). Over the past 10 years, more than 88 300 hours have been spent on eliminating AC that occurred in wells in the offshore fields of Azerbaijan alone. In total, 54 wells were abandoned (Dadashov and Abyshov, 2012).

This article proposes a method that can quickly detect AHRP high-pressure zones based on the well's MPD.

Methodology and materials

The following are the methods for assessing, predicting, and quickly detecting formation or pore pressure anomalies during the drilling process: geophysical data from wells, identification of mechanical drilling parameter (MPD) values that exceed acceptable limits, and identifying patterns of change in MPD relationships. Although the accuracy of predictions using the first method is high compared to other methods, predictive data is obtained with some time delay, usually requiring a series of complex and expensive logging operations and drilling stops to collect the data.

For the second method in most cases, detections are made by simple technical means or visually by the drilling crew and have low accuracy. The third method has a higher detection accuracy than the previous group.

The methods included in the last two groups have a number of advantages: data is obtained online (some methods have a certain delay), and most importantly, it does not require stopping drilling, etc. Although the accuracy of the methods included in the last group is higher than that of methods of the previous group, their technical implementation as detection devices (systems) is quite complex. The operating principle of these systems is based on calculations using formulas formed on the basis of mathematical formalization of the patterns of changes in dependencies between the MPD and allows a fully automated forecasting process. However, the lithological instability of rocks reduces the detection accuracy of these methods. Therefore, in order to improve the accuracy of the system, along with the proposed method, one or more of the simple MPD prediction methods shown below can be used (Kerimov et al., 2014; Korotayev et al., 2017):

- torque drilling tool (DT) (real-time method);
- increased load on the hook (real-time method);
- drilling mud (DM) pump outlet pressure (delayed method);
- change in gas content, density, level of DM in the receiving tank (delayed method);
- DM temperature at the wellhead (delayed method).

The dependence of the mechanical drilling speed (MDS) on the MPD and the drilling properties of rocks has been known to specialists since the middle of the last century. In general terms, this dependence can be expressed as follows:

$$V_{mex} = nf_1(P_y/D_{qa}) \cdot f_2(V_{fs}) \cdot f_3(T_{qa}) \cdot f_4(\Delta_p) \tag{1}$$

where:

V_{mex} – mechanical drilling speed,

n – a coefficient reflecting the characteristics of the drillability of rocks,

$f_1(P_y/D_{qa})$ – a function characterizing the influence of the load on the drilling tool and the diameter of the drilling tool,

$f_2(V_{fs})$ – a function characterizing the influence of the rotation speed of the drilling tool,

$f_3(T_{qa})$ – a function that takes into account the blunting of the drilling tool,

$f_4(\Delta_p)$ – a function taking into account the differential pressure.

The first mathematical formalization of the dependence between some MPDs was given by Bingham (1965) with the following formula:

$$V_{mex} = a\,(V_{fs}/D_{qa})^d \tag{2}$$

where:

V_{mex} – MDS [ft/min],

V_{fs} – DT rotation speed (DTRS) [cycle/min],

D_{qa} – DT diameter [inches],

a – lithological coefficient,

d – index (exponent) of rock density exponent.

Two years later, mathematicians Jorden and Shirley (1966) solved the above mathematical equation using the d-exponent. They also included coefficients that took into account the units of measurement used in the US oil industry at that time. Under the condition $a = 1$ (in the case of unchanged lithological conditions), they obtained the following formula for the d-exponent (hereinafter, d) (Jorden and Shirley, 1966):

$$d \approx \frac{\lg\left(\dfrac{V_{mex}}{18V_{fs}}\right)}{\lg\left(\dfrac{0.067P_y}{D_{qa}}\right)} \tag{3}$$

where:

V_{mex} – mechanical drilling speed [ft/min],

V_{fs} – drilling tool rotation speed [cycle/min],

P_y – load on drilling tool [pound],

D_{qa} – diameter drilling tool [inch].

An analysis of this formula shows that the d function allows one to track the degree of compaction/porosity and differential pressure. In other words, there is a strong correlation between reservoir pressure and the parameters V_{mex} and d: by changing the value of d when porous formations are opened it is possible to estimate abnormally high reservoir pressures and detect these zones. Idealized graphs of this relationship are shown in Figures 1 and 2, where H – is the well depth.

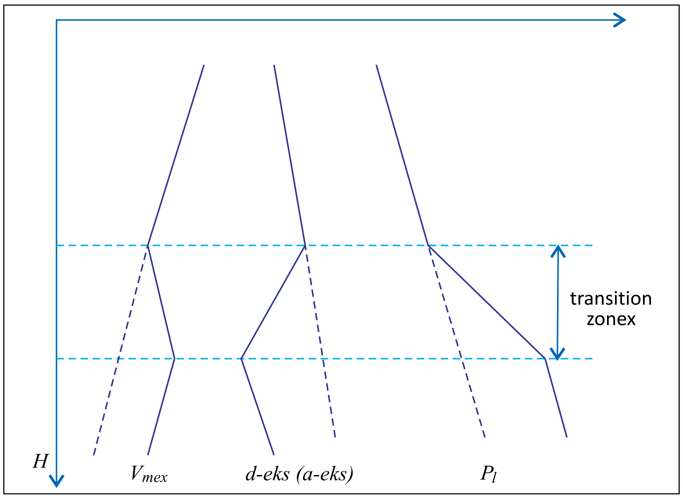

Figure 1. Correlation between parameters V_{mex}, d, P_l (Mouchet and Mitchell, 1989)

Rysunek 1. Korelacja pomiędzy parametrami V_{mex}, d, P_l (Mouchet i Mitchell, 1989)

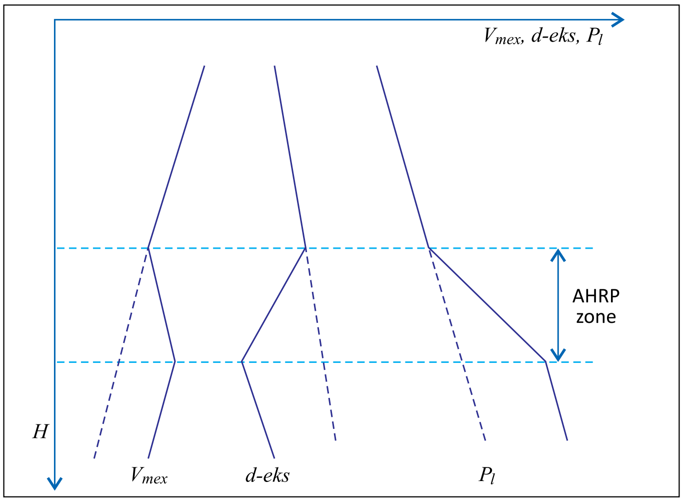

Figure 2. Correlation between parameters V_{mex}, d-exs, P_l (Mouchet and Mitchell, 1989)

Rysunek 2. Korelacja pomiędzy parametrami V_{mex}, d-exs, P_l (Mouchet i Mitchell, 1989)

As can be seen from the graph, in normal mode, with increasing depth, the reservoir pressure increases along the "normal compaction curve", and the MSD decreases linearly in an inversely proportional manner. Accordingly, the value of function d increases. From the moment the porous layers are opened (abnormally high reservoir pressure AHRP), the reservoir pressure P_l increases sharply and the rocks are drilled faster, i.e., V_{mex} sharply increases. In accordance with the change in these parameters, the value of the function *d* monotonically decreases throughout the entire high-pressure zone. Therefore, this pattern between MPDs can be used to estimate high reservoir pressure and detect high-pressure zones.

The proposed *d*-exponent function remained practically the only method for detecting high-pressure zones for several decades. This method was subsequently improved by other authors and dozens of variants were developed. The main goal of the improvement work was to increase the accuracy of the forecast of systems created on the basis of this method. Because the dynamics of the increase or decrease in MDS values can be changed and masked by the influence of many other factors, for example, the lithological composition of rocks (the main influencing factor), the hydraulic characteristics of drilling tools (for example, the degree of blunting), etc. Therefore, systems created using dependencies between mechanical drilling parameters are usually used in fields where the lithological structure of rocks is quite stable (for example, in the Baku archipelago and in the South Caspian depression (Parisa, 2016). Also, the accuracy of the data specified in the design documentation for well construction, such as lithological and stratigraphic characteristics of the well, expected complications, drilling fluid density (on the combined pressure graph), as well as equivalent pressure gradients (on the pressure graph), taking into account the practical results of drilling wells, proximity, etc. are important factors. In addition, to increase accuracy, one or more simple detection methods belonging to Group 2 can be used together with the proposed method. However, despite its shortcomings, the method is still widely used today.

Discussion and conclusions

The authors, as part of a working group, have developed several methods for detecting zones of abnormal pressure. Two of these methods are protected by copyright certificates. These methods are based on the principle of detecting a change (decrease) in fluid density as a result of gas leakage into the drilling mud (Makhmudov et al., 1984) and deviation of the mechanical drilling AHRP speed from the probable limit (Makhmudov et al., 1985) as a result of high pressure. Devices created based on these methods were implemented in the oil and gas production department named after Narimanov (Baku, Sangachal settlement) of the "Azneft" Production Association and demonstrated high efficiency (Socar). Last year, within the framework of a grant project (21 LR-ANAS), implemented with the financial support of the SOCAR Science Foundation, another improved version of the classical *d*-exponent (α-exponent) method was developed, and the prototype system created on this basis was tested by conducting laboratory experiments using computer modeling (SOCAR Science Foundation). The research results were presented at an international conference (Agaev et al., 2022). The relationships between the mechanical drilling speed and other MPDs were used in the development of the method. The mathematical expression of the method is as follows:

$$\alpha = \frac{\lg \dfrac{V_{mex}}{60V_{fs}}}{\lg \dfrac{P_y}{\rho_{qm} D_{qa}^2}} \tag{4}$$

where:
V_{mex} – mechanical drilling speed [m/h],
V_{fs} – drilling tool rotation speed [vol/min],
P_y – load on drilling tool [kg],
ρ_{qm} – denotes the drilling fluid density [kg/cm^3],
D_{qa} – diameter of the drilling tool [m].

It is worth noting that the formula includes the DM density parameter. This makes it possible to calculate the required DM density using equations (5) and (6) to restore ($P_{hidst} = (1–1.3P_l)$ the disturbed pressure balance ($–\Delta P$) between hydrostatic and reservoir pressure after detecting a high-pressure zone using the function:

$$\rho_{qm} = \frac{P_y}{10^n D_{qa}^2} \tag{5}$$

where:

$$n = \frac{lg \dfrac{V_{mex}}{60V_{fs}}}{\alpha_{max}} \tag{6}$$

The principle of detecting AHRP high pressure zones using the method is better seen in Figure 3.

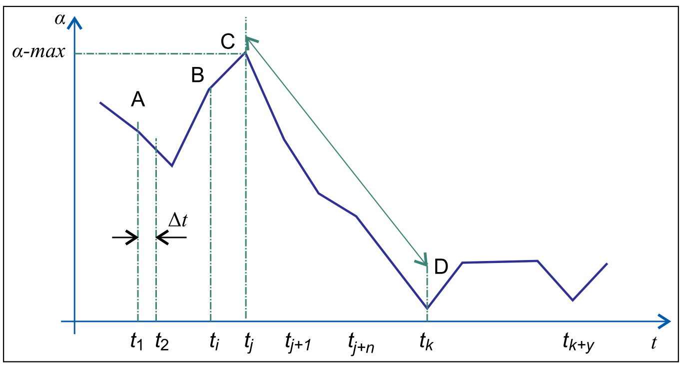

Figure 3. AHRP zone identification chart
Rysunek 3. Wykres identyfikacji strefy AHRP

As mentioned above, if the drilling process continues under conditions of normal reservoir pressure, the average value of α increases monotonically with increasing depth (small amplitude deviations are not taken into account). From the moment the DT opens the AHRP porous zone, MDS increases sharply, and accordingly, the value of α monotonically decreases by m times over a certain period $N\Delta t$. (Δt is the reciprocal value of the sampling frequency of the MPD sensors). The value of m is selected experimentally depending on the thickness of the formation, drilling mode, and other parameters specified in the well design documentation. During the period t_1–t_j on the graph, the value of $\boldsymbol{\alpha}$ decreased only by half (for $2\Delta t$, $N = 2$) and is not considered as a case of detecting an anomalous zone, since it is less than $\boldsymbol{m}$. Since the value of α in the CD section (in the t_j–t_k interval) continuously decreases by $N \geq m$ times, the formation drilled during this period is identified as the initial section AHRP zone. From this point on, the density of the weighted DM to counteract the abnormal pressure is calculated using the derived equations (5) and (6).

Based on the proposed method, an operating algorithm (Figure 4) and a control program in the C++ programming language were developed. The manipulation of the system operation is verified by experiments carried out using computer simulation. An array formed from real MDP values obtained from wells drilled during the implementation of the grant project was used as input data. This data is entered into the system manually in two ways: sequentially for each calculation session or as a block of data placed in the program code for automatic entry.

MPDs are received from the sensors of the digital equipment installed on the well platform to the unit that generates the input signals of the system, where they undergo preliminary processing (cleaning from interference, generating pulses, formatting in accordance with the requirements of the input-output protocols of the computer, etc.). From here, the signals are sent to the input of the computing device, and the system is started: the value of the function a is calculated based on the current values of the MPD, and is output to the driller's control panel (DCP). The calculation cycle is repeated until the value of the function a decreases consistently and monotonically by $m = mt$ times. At the same time, sound and light warning signals are transmitted to the control center. From this moment on, the system calculates the required DM density using the current values of the function arguments, and α-max, taken from the sequence of values a, using formulas (5) and (6). The result is displayed on the DCP. Below is a part of the program developed according to the specified algorithm for calculating the value of function a for the periods of the **label1** and **label2** commands.

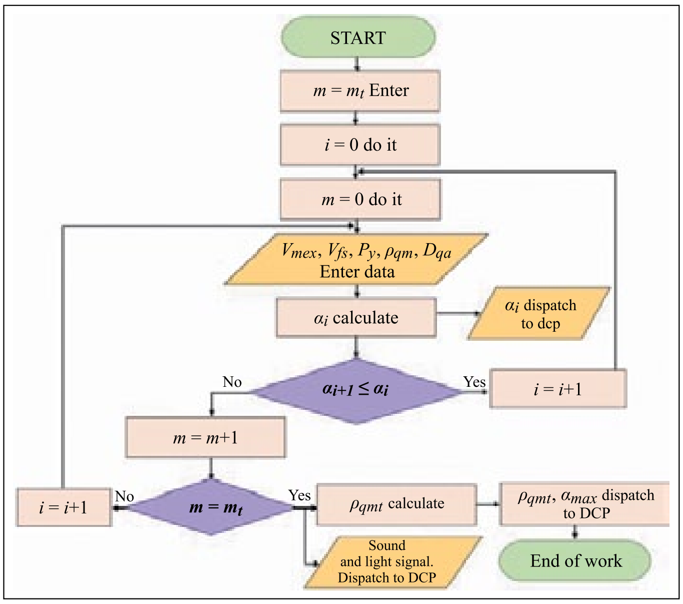

Figure 4. System operation algorithm
Rysunek 4. Algorytm działania systemu

Note: The designations of formula and algorithm parameters have been changed in the program code in accordance with the requirements of the C++ programming language:
V_{mex} = **Vmex**; V_{fs} = **Vfsc**; P_y = **Py**; ρ_{qm} = **Roqm** (required density drilling fluid (DF)); D_{qa} = **Dqa**; $\alpha_{\max}$ = **alfamax**; m_t = **mteleb**; α_i = **alfai** ($\boldsymbol{\alpha_i}$ – current function value – $\boldsymbol{a}$).

```
#include <iostream>
#include <cmath>
#include <windows.h>
using namespace std;
float Vmex, Vfsc, Py, Dqa, Roqm;
float nn, Roqmt, alfai=0.0, alfaiyeni, alfamax=-100.0;
int i, m, mteleb;
int main() {
  label_start:
  cout << "\n label_start - Вводите mtələb:  ";
  cin >> mteleb;
  i = 0;
  label1:
  std::cout<<"Label1" ;
  m = 0;
  std::cout <<"   m = "<<m;
  label2:
  std::cout<<"\nLabel2" ;
  std::cout << "\n Mechanical drilling speed - m/h: ";
  std::cin >>Vmex;
  std::cout << "\n Drilling tool rotation speed – rev/min: ";
  std::cin >> Vfsc;
  std::cout << "\n Load on drilling tool - kg: ";
  std::cin >> Py;
   std::cout <<"\n Denotes the drilling fluid density, kg/cm³: ";
  std::cin >> Roqm;
  std::cout << "\n  Drilling tool diameter - cm: ";
  std::cin >> Dqa;
```

```
alfaiyeni = (log10(Vmex / (60 * Vfsc))) / log10((Py) /
(Roqm * Dqa * Dqa));
alfaiyeni = abs(alfaiyeni);
if (alfai==0.0) {alfai = alfaiyeni;}
std::cout << " i=" << i << "  alfaiyeni= " << alfaiyeni
<< "\n ";
```

Note that the accuracy of the forecast of this group of systems mainly depends on the accuracy class of digital devices that measure the DM density. Currently, such devices with different functionality (and price) are produced in many countries.

Conclusions

The article discusses the issues of detecting high pressure zones when drilling oil and gas wells. The importance of detecting these AHRP zones is substantiated in order to prevent accidents and complications caused by abnormal reservoir pressure and to increase the efficiency of oil operations. An improved version of the classic *d*-exponential method for detecting AHRP high-pressure zones is proposed. The method additionally calculates the density of the drilling fluid required to compensate for abnormal pressure. It is proposed to use this method in oil and gas fields with fairly stable lithology. The parallel use of several methods to improve the accuracy of system detection is also justified. An algorithm for the operation of a system created on the basis of this method has been developed, and a control program has been written in the C++ programming language. The system's performance was tested in laboratory experiments using computer modeling.

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