Problem analysis of geotechnical well drilling in complex environment

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Abstract. The article examines primary causes of problems occurring during the drilling of geotechnical wells (injection, production and monitoring wells) for in-situ leaching to extract uranium in South Kazakhstan. Such a drilling problem as hole caving which is basically caused by various chemical and physical factors (hydraulic, mechanical, etc.) has been thoroughly investigated. The analysis of packing causes has revealed that this problem usually occurs because of insufficient amount of drilling mud being associated with small cross section downward flow and relatively large cross section upward flow. This is explained by the fact that when spear bores are used to drill clay rocks, cutting size is usually rather big and there is a risk for clay particles to coagulate.

1. Introduction
Based on the analysis of geological environment as well as the methods and technology used to drill both exploration and geotechnical wells (injection, production and monitoring wells) at uranium sites owned by “Volkovgeologiya” JSC, the most common drilling problems caused by various factors have been revealed. The present article examines the most serious drilling problems – hole caving and packing.

Hole cave-in and hole collapse can be caused by any borehole instabilities stemming from in-situ rock stress. Therefore, in order to select an appropriate drilling technology involving well design and development of preventive measures and adequate emergency response plans, it is essential to evaluate mechanical behavior of subsurface rocks.

2. Materials and methods
In accordance with the rock classification based on the mechanical behavior modes [1], the rock formations which comprise the geological cross-section of Khorasan-2 and South Karamurun uranium deposits are classified as poorly stable or unstable and presented by the following rock types: weak unconsolidated rocks, plastic, soft and loose rocks related to the corresponding drillability categories from 1 to 1Y. As is shown in figures 1 and 2, hole caves are formed while drilling sand and clay formations.

Apart from the above-mentioned, the rock stability can be estimated by cavernosity ratio proposed by K.F. Paus [1]:
\[ K = \frac{V_a}{V_c} = \frac{d_a^2}{d_c^2}, \]  

(1)

where, \( K \) - cavernosity ratio;
\( V_a \) and \( V_c \) – actual and calculated hole volumes;
\( d_a \) and \( d_c \) – hole diameter and the diameter of applied cutting tool.

The rocks are considered stable, if \( K = 1 \), temporary stable rocks if \( 1 < K < 3 \) and unstable if \( K > 3 \). When \( K < 1 \), forces acting within the formation push the wall of the hole inward, for example while drilling swelling clays.

While drilling the sand formations in Khorasan-2 uranium deposit, the calculated diameter is 132 mm and actual one is 230 mm (figure 1). Under these conditions, cavernosity ratio is assumed to be 3.04, which means that these rocks are referred to as unstable.

![Figure 1. Caliper logs of wells № 5-6-17-18](image)

While drilling the sand formations in South Karamurun uranium deposit (figure 2), the diameter of applied cutting tool is 161 mm and the actual diameter is up to 311 mm. In this case, cavernosity ratio is assumed to be 3.74, which characterizes the rock formation being drilled as very unstable.
It is worth noting that dry heavy clays are considered to be stable rock. That air-rotary drilling is primarily used for drilling in such formations proves the above-mentioned fact [2]. Under these conditions, hole cave is formed due to different reasons which will be further discussed.

As previously mentioned, in-situ overburden stress directly affects hole cave formation, which in its turn may lead to borehole collapse. Because of the in-situ overburden stress, soft loose, unconsolidated, fractured and broken rocks push the hole wall outward. The value of overburden stress is defined by the following formula [3]:

\[ P_{\omega} = g \cdot \rho_m \cdot H, \]  \hspace{1cm} (2)

where \( P \) – overburden stress value, Pa;
\( \rho_m \) - rock density, \( t/m^3 \);
\( H \) - formation depth, m;
\( g \) - gravity acceleration, m/s\(^2\).

Here, it is essential to consider horizontal stress value which is obviously dependent on overburden stress.

The value of horizontal stress is determined by [3]:

\[ P_\varphi = \frac{\mu}{1 - \mu} P_{\omega}, \]  \hspace{1cm} (3)

where \( P_\varphi \) - horizontal stress value, Pa;
\( \mu \) - Poisson ratio (for clays \( \mu = 0.2 - 0.4 \)).

Besides, mud hydrostatic forces are also used to prevent formation collapse. The value of hydrostatic head can be calculated by the following formula [3]:

\[ P_\omega = g \cdot \rho_m \cdot H, \]  \hspace{1cm} (4)

where \( P \) – mud hydrostatic head value, Pa;
\( \rho_m \) - drilling mud weight, \( t/m^3 \);
\( H \) - the depth where hydrostatic head is measured, m;
\( g \) - gravity acceleration, m/s\(^2\).

Generally, borehole fails when horizontal stress exceeds the tensile strength of the rock and hydrostatic mud head, which is expressed as follows:
where, $\sigma_T$ - rock tensile strength, Pa.

Thus, in order to ensure borehole stability, it is required to observe the following conditions:

$$P_\delta \geq \sigma_T + P_\infty$$

(5)

The above-mentioned formula fully describes hole cave development and represents almost all factors which influence this process, i.e. overburden stress value, rock mechanical properties and hydrostatic head of mud.

Mud-circulating drilling can also alter rock properties through the interaction with fluid, which in its turn influences borehole stability parameters. Under these conditions, the stability of the borehole is directly dependent on the moisture content.

Drilling mud/clay rock interaction occurs through adsorbing fluid filtrate. Depending on the moisture content, i.e. swelling potential, some authors [2] distinguish the following types of rocks: slightly swelling rock, medium swelling rock and strongly swelling rock.

When the rock moisture content is low, the boreholes are rather stable and there are no serious drilling problems.

While drilling medium swelling clay, the drilling mud/clay interaction causes the clay to swell, weaken, and eventually fall into the wellbore, which can cause tight hole conditions, however, without cave development. If the borehole diameter is small, the drilling mud/clay interaction can lead to total collapse and loss of the hole.

Drilling of strongly swelling clays presents the greatest engineering challenge in terms of cave development. In this case, pressure decreases the strength of clay by destroying cement bond between the clay platelets (clay dispersion). The clay becomes ductile and is pushed by the overburden stress to the wellbore developing the caves.

To illustrate the above-mentioned borehole stability parameters, the example of cave development while drilling wells №3-109b is provided. In accordance with the caliper log shown in figure 2 caves basically develop while drilling through clays and siltstone. The largest cave was found at the depth of 328-460 m, with cave diameter being 311 mm.

Let us define the overburden stress value by the dependence (2) if the conditions are as follows:

well depth - 382 m, clay density - 2500 kg/m$^3$ and gravity acceleration - 9.81 m/s$^2$. It can be expressed as follows:

$$P_s = 9.81 \times 2500 \times 382 = 9368550 \text{ Pa} = 9.4 \text{ MPa}.$$  

Then, it is necessary to define the value of horizontal stress by the following dependence (3):

$$P_\delta = 9.4 \times \frac{0.25}{1 - 0.25} = \frac{0.98}{0.75} = 3.14 \text{ MPa}.$$  

The hydrostatic head of the mud column is determined by the dependence (4), with the density being 1030 kg/m$^3$. At this depth, hydrostatic head is as follows:

$$P_\infty = 9.81 \times 1030 \times 382 = 3859843 \text{ Pa} = 3.9 \text{ MPa}.$$  

Thus, with the clay yield point being 2-14 MPa and hydrostatic head being 3.9 MPa, borehole walls should have been stable as the sum of all the factors mentioned above exceeds the horizontal stress by 3,1 MPa. This conclusion is especially relevant for dry clays; however, even in case when clay strength equals zero, borehole walls should have remained stable as hydrostatic head exceeds the
horizontal stress. Therefore, these caves developed due to chemical reactions caused by the exposure of the rock to the drilling mud, which altered physico-mechanical properties of rocks.

When humidified, the strength of clays characterized by high porosity significantly decreases as they are the most water-saturated rocks. Increasing water content weakens clay rocks. It is explained by the alteration of rock physico-mechanical properties, precisely, the dissolution of grain-to-grain cement bond.

In addition to the above-mentioned causes, the development of the caves of large diameter while drilling geotechnical well №3-109b can be explained by other reasons as well. In accordance with the selected drilling technology, hard rock formations were drilled by PDC bits being 132 mm in diameter, while soft rock formations were drilled by spear borers and roller bits 161 mm in diameter.

Figure 3 illustrates the principle of large cave development while drilling the above-mentioned well.

![Figure 3. Cave development principle](image)

In our opinion, due to the fact that there is great difference in drilling rate for soft rocks and hard rocks (soft rocks – 15-20 m/hr; hard rocks -0.20-0.30m/hr ), the penetration rate drastically decreases when a drill bit penetrates into hard rock formation, which in its turn increases mudflow intensity near the drill bit. This leads to hole washout problems and large cave formation. The development of small caves while drilling the overlying soft formations can be explained by the presence of hard streaks where the drilling rate also decreases which results in washout enlargement due to by excessive bit jet velocity.

3. Results and discussion

Based on the above-mentioned facts, it is possible to conclude that while drilling geotechnical wells at uranium sites in South Kazakhstan, hole cave development is caused by the mud filtrate invasion in clay rocks (clays, siltstone, etc.) and excessive bit jet velocity.

Packing is another typical drilling problem which is related to borehole instability and poor hole cleaning. As mentioned above, packing leads to excessive torque and drag on drill string, as well as difficulties in logging, particularly in running logging tools into the borehole, and cementing. All this increases mud and cementing costs. For example, the injection well № 3-109b in North Karamurun uranium deposit was drilled according to the following procedure: spear borers of 161 mm in diameter were used up to the depth of 460 m, then the rock formations were drilled by PDC bits being 132 mm in diameter up to the target depth – 550 m. When well logging was being performed, logging tool got stuck at the depth of 397.3 m. To find out the reason, caliper log was examined.
4. Conclusion
The caliper log analysis has revealed that a large cave occurs at the depth of 378 m-460 m, being 311 mm in diameter and 80 m in thickness.

It is obvious that such a cave negatively influences hole cleaning performance due to the sharp decrease in drilling mud return velocity, which in its turn results in cutting accumulation. When the pump is stopped, cuttings fall back into the well bore causing pack-off in tight section of the hole (change in diameter from 161 mm to 132 mm) and, thus, preventing a logging tool from running into the wellbore.

Besides, in order to prevent clay rock dispersion, chemical reagent coagulator K-ION has been introduced into the drilling mud. This reagent forces the cutting particles to coagulate forming clay balls or packing. A further core drilling of packing has revealed that it mostly consists of clay rocks and is of plastic character.

It should be also mentioned that suspending clay platelets, i.e. packing, usually accumulate on bit surface (above the cutting tool or in place of drill pipe connections), which leads to hole drag with corresponding negative effects: stuck pipe and drill string failures, increased power consumption, etc.

Thus, packing results in significant operational problems, most of them being related to well design and drilling. The liquidation of these drilling problems leads substantial financial losses. As it became apparent, packing is basically caused by hole caves and insufficient amount of drilling mud which ensures the required velocity of mud returns in caves.

References

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