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MECHANISM OF CAVING WHILE DRILLING THROUGH HIGHLY DISPERSIBLE ARGILLACEOUS FORMATIONS

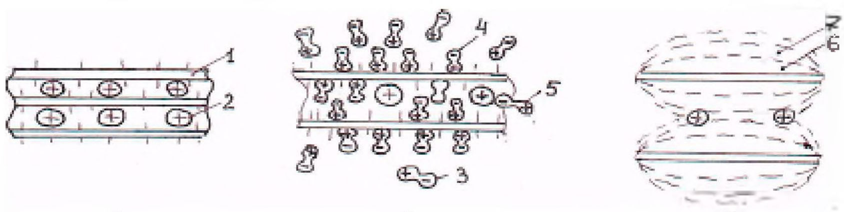
Дано теоретическое объяснение явления кавернообразования в стволе скважины, пробуренной по глинам либо иным глинистым породам. Установлено, что среди многих причин этого явления наиболее важная связана с колебаниями давления в стволе скважины, вызванными преимущественно технологическими факторами. Сделаны некоторые простые рекомендации по улучшению положения. Осложнения при бурении скважин обусловлены структурой глинистых пород. Напряжения, вызванные набуханием прискважинного влажного слоя, ведут к отслаиванию его участков с выравниванием давления жидкости по обе их стороны. Импульс к обвалам дают динамические составляющие скважинного давления. Даны рекомендации по ослаблению их воздействия.
Ключевые слова: бурение, пучащиеся глины, кавернообразование.

Мақаланың мақсаты - саз және сазды жыныстарды бұрғылау кезінде ұңғы қабырғасында пайда болатын қуыс-қолтық құбылысын теориялық тұрғыдан түсіндіру. Мақалада бұл құбылыстың басқа да көптеген себептерімен қатар, ең маңыздысы ұңғы қабырғасындағы қысымның тербелуі әсерінен болатындығы анықталды және көрсетілді. Тербелу технологиялық факторлар әсерінен болады. Жағдайды жақсарту бойынша бірнеше қарапайым және көрнекті (себебі жалпы жағдай анық болды) ұсыныстар жасалды. Нәтижелерді практикалық бағалау ары қарайғы зерттеулер барысында жасалады. Ұңғыны бұрғылау кезінде болатын апаттар көбіне сазды жыныстардың құрылымына байланысты болады. Ұңғы ішіндегі сұйық қысымы қабат қысымымен тепе-тең болмаса, сазды жыныстардың сұйық әсерінен ісінуі оның қабаттарының қатпарлануына әкеліп соғады. Ұңғы қабырғасының опырылуына оның ішіндегі қысым динамикасы тікелей әсер етеді.

Осы қысым динамикасының әсерін төмендету ұсынылып отыр.
Кілт сөздер: бұрғылау; борпылдақ саздар, қуыс-қолтық пайда болуы.

The objective of the paper is to provide a theoretical explanation of the phenomenon of caving in well-bore, drilled through clays and other argillaceous formations. It was established and shown in the paper, that among many other causes of this phenomenon one of the most important is associated with fluctuations of the down hole pressure, which are caused primarily by technological factors. Some simple and obvious (since the general picture became much more clear) suggestions on improvements in the existing technology are made. The evaluation of their practical results is to be made in the course of further research. Aggravations while drilling wells are caused by the structure of clay formations. Stresses that are linked with the process of bulging of the wet well bore zone thickness of clays are conductive to scaling off some segments of that thickness and equalizing the pression on both sides of those segments.
Key words: drilling, bulging clays, caving.

About 70 % of formations in geological structure of South Kazakhstan uranium deposits are clays and argillaceous rocks. They are notable for their high capacity of dissolving in water based drilling muds - a property that has brought about many aggravations and failures in drilling process.



A B C

Fig .1. Scheme of the argillaceous rocks' structural packet: A – in dry state; B – in an early stage of contact with water; C – after hydration; 1 – elementary lamella of negative charge; 2 – ion of metal; 3 – water molecule (dipole); 4 – dipole, connected to lamella; 5 – dipole, connected to an ion of metal; 6 – first layer of hydrate envelope ; 7 – second layer

It is established [1] that microstructure of clays is represented by packets of tiny lamellae 1 (fig. 1 A), possessing small (fractures of micron) thickness and relatively very large surface, to which corresponds high surface energy. The energy manifests itself through a negative electrical charge. As all the elementary lamellae possess the negative carge, they tend to repulse each other and destroy the elementary packet. However it does not happen because the lamellae are tightly held in the packet by positively charged ions 2 of metals. Often the ions are those of sodium or calcium. The magnitude of the ions' charge is characterized by their valence. The valence of calcium equals two, while that of sodium - one. That accounts for the fact, that the calcium clay structural packets are stronger, than the sodium clay ones, which are easier to dissolve (disperse) in water.

As a result of penetrating the mountain rock by a well (fig. 2A) a confining pressure free zone is formed around the well bore [2].

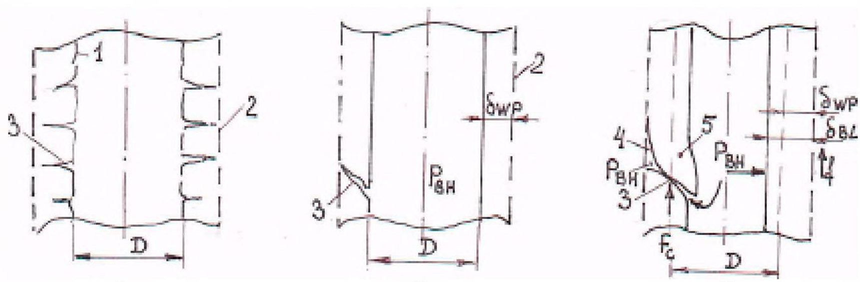


Fig. 2. Processes, developing in clays, penetrated by a well: A – well bore zone, free of confining pressure; B – a crack in that zone before the bulging process has developed; C – the same crack under the bulging stress; 1 – bore hole walls; 2 – border of well bore zone; 3 – a radial (crosswise) crack; 4 – a lengthwise crack, 5 – a scaling off segment of the wet layer; P_{BH} - bore hole pressure; D - bit diameter; δ_{WP} - depth of water penetration; δ_{BL} - thickness of the bulging wet layer; F_C - force, caused by compression stress; f - friction force

Were it not so, drilling through soft formations with air blasting (and no hydrostatic pressure), would not be possible, because of sloughing of the hole's walls - which actually does not happen. Disappearance of confining pressure in the well bore zone causes opening of cracks and pores, through which under the bore hole pressure P_{BH} water from water based drilling mud enters. Water molecules 3 (fig. 1 B) have an elongated form, at one end of which a positive electrical charge being concentrated, at another - a negative one. Such molecules are named dipoles. The dipoles 4 with their positive pole are attracted to the negative charged surface of the elementary lamellae. Taken together all such dipoles create a hydrate envelope 6. In the envelope the dipoles are capable to be arranged in many layers. The greater is the electrical charge of the lamella, the more layers can have its hydrate envelope. However the number of the layers also depends on inflow of water. That number and, consequently, the thickness of the hydrate envelopes grows in proportion with arrival of new dipoles. Overcoming the holding together force of the positive ions of metals, the envelopes grow and push the lamellae apart. Besides, some of the ions are extracted out of the structural packets by the dipoles 5, which engage them with their negative pole. The clays' structure disintegrates.

The extent of disintegration depends on quantity of water, the clay can be in contact with. That quantity is practically unlimited in case of drilling cuttings, and they disperse up to of full destruction of structural packets. The elementary lamellae are losing connection with each other and become components of drilling mud, increasing its density and viscosity. Unlike that, quantity of water, penetrating into the well bore zone is limited. It depends on permeability of cracks and pores, as well as on the pressure and properties of filter cake. So, instead of ultimate dissolution, a growth of elementary lamellae's hydrate envelopes is taking place, and as a result - a bulging of the wet layer.

According to V.D. Gorodnov [3] the volume of a piece of clay, held in a vessel with water, can after elapsing of a certain time period increase fivefold and more. However unlike conditions of the experiment, where the piece of clay can expand equally in any direction, expanding of clay in the well bore zone is limited. The wet layer can expand in radial direction, thus reducing the well bore's cross section area. The limiting factor here is the well bore pressure P_{BH}.

Extending of the wet layer along the axis of the well looks in a first approximation impossible. Indeed, extending of any segment of that layer can take place only at the expense of neighboring segments - situated above and below the segment in question, and all the segments of the wet layer being similar in every respect. However a more intense consideration leads to a conclusion that equal strength of neighboring sectors is possible only when certain requirements are satisfied. They are:

- Equal thickness of the wet layer;
- Absence of breaches of entirety (like cracks)
- Absence of contacts with rocks of different solidity

At the fig. 2 a crack 3 is demonstrated, which is passing at some inclination to the well's radial cross section. Such cracks may arise at the stage of removal of the confining pressure, brought about by the clay's massive having been penetrated by the well (as it was mentioned above). However they may also be originated later by all sorts of deformations in the bulging wet layer.

As a result of obstacles to extending, there arise compression stresses in the clay's wet layer. They create a longitudinal force F_C, acting upon the crack's inclined surface. The force can be resolved [4] in such a way, that one of its components should act upon the segment 5 of the clay's wet layer down along the crack's surface, while another - perpendicularly to it. For that reason the sector 5, extending, slides down along the crack, and, while doing that, it scales off the contact with the dry massive of clay, producing a longitudinal crack 4. As it is shown by arrow on the figure 2 C, the drilling mud, being under pressure P_{BH}, moves along the crack 3 into the crack 4. After having filled it, the mud creates there the pressure P_{BH} - the same as in the well bore.

It is important to observe, that normally the pressure P_{BH} is acting upon the wet layer area from inside the well bore only. Therefore, it is pressing the wet layer against the dry massive and creating a friction force f, which acts against the possible caving . But the crack 4 equalizes pressure at both sides of the wet layer, and with that crack's coming to being, the segment 5 becomes in fact suspended - to the detriment of stability of the bore hole walls.

At the beginning of the scaling off process the length of the crack 4 and, correspondingly, that of the suspended segment 5 can be not very significant. Besides, due to wet clay's plasticity, the crack is unlikely to develop without some outside interference. After having lost its connection with the dry massive, the scaling off segment can still continue to be in its place through its links with the neighboring segments, whose connections with the dry massive are preserved. Nevertheless the situation continues its development towards caving.

As it is well known, the bore hole pressure:

$$p_{BH} = p_{HS} + p_{HD}, \tag{1}$$

where p_{HS} and p_{HD} - are correspondingly hydrostatic and hydrodynamic components. The first one:

$$p_{HS} = 9.81\,\rho H, \tag{2}$$

where ρ is density of drilling mud, and *H* depth of clay interval in question. Ordinarily during the trip p_{HS} is growing relatively slowly and continuously. There may be various kinds of hydrodynamic components, but in the course of drilling process one is inevitably present - that is pressure drop on the ascending flow of the flushing fluid:

$$p_{HD} = p_{LF} + p_{\Delta\rho}, \tag{3}$$

where p_{LF} - pressure drop, caused be friction forces in the liquid, while $p_{\Delta\rho}$ - pressure drop, caused by difference of densities between ascending - containing cuttings, and descending - clean, flows.

According to Darsi formula in annular space - where the ascending flow moves:

$$p_{LF} = \lambda \rho_{AF} H \frac{V^2}{2(D-d)}, \tag{4}$$

where λ - is hydraulic resistance factor;

D and d - outer and inner diameters of the annular space;

V - velocity of the ascending flow.

The component, depending on density difference

$$p_{\Delta\rho} = 9.81(\rho_{AF} - \rho_{DF})H, \quad (5)$$

where ρ_{AF} and ρ_{DF} - densities of the ascending and descending flows correspondingly.

According to formula (1), both p_{HS}, and p_{HD} are present during the drilling process. But periodically that process is interrupted with drill string connections operation, when the flushing liquid circulation has to de stopped. At that moment in the well bore component p_{HD}, as presented by the formula (3), disappears and formula (1) becomes reduced to:

$$p_{BH} = p_{HS} \quad (6)$$

Here it must be taken into account, that in the crack 4 transition from the "old" high value of P_{BH}, to its "new", lower one, cannot be effected without time expenditures. Those last result from the fact, that for lowering pressure in the crack 4 up to its new value in the well bore, some quantity of mud has to travel from that crack through the crack 3 back to the well bore. And the way of traveling represents a certain hydraulic resistance. What follows from those arguments is a conclusion, that up to the end of pressure equalizing time the pressure in the crack 4 remains higher than in the well bore. The pressure difference originates a force F_T, tending to tear the segment 5 from the dry massive, or at least to increase the "free" - not contacting with the dry massive - area S_F of that segment.

Thus, at the very moment of circulation cessation the off-scaling force, bearing upon the segment 5:

$$F_T = S_F p_{HD}, \quad (7)$$

where p_{HD} - the vanishing hydrodynamic component of p_{BH}.

After making connections and resuming the circulation p_{HD} appears again, and for some tine the well bore pressure prevails over that in the crack. However the increase of S_F, obtained, while performing connections, remains.

At the department of drilling technology of the Kazakh Satpajev Science and Technology University a computer model of well's flushing liquid circulation system was worked out. By means of that model an assessment of pressures p_{HS} , p_{HD} and p_{BH} was made for typical conditions of drilling wells at uranium deposits. The reference data are as follows:

– Depth of dispersible clay occurrence = 400 m

– Bit diameter D = 0,161 m

– Drill pipe diameter d = 0,089 м;

– Drilling mud specifications: density ρ = 1100 кg/м^3 ; viscosity η = 0.01 Pa*c;

Dynamic shear stress τ = 10 Pa

– Penetration rate $V_Б$ = 15 m/h

The program's outputs under such conditions were:

– Optimum drilling mud flow rate Q = 0,00688 m /c

– Ascending flow velocity V = 0,487 м/c.

– Total pressure drops - on the mud pump's manometer $p_м$ = = 0.85 MPa.

– Pressure drops on the ascending flow p_{HD} = 0,27 MPa

– Hydrostatic pressure p_{HS} = 4,16 MPa.

– Total pressure in the well bore p_{BH} = 4.43 MPa If, for example, the scaled off area of the sector 5

S_F = 0,0001 m^2 (1 cm^2), and (as established above) p_{HD} = = 0,27 MPa, then, formula (7) gives the scaling off force F_T = 27 H. That value corresponds to the moment of circulation cessation and is therefore a maximum one. In a matter of few fractions of a second the force comes down to zero. But, on the other hand, for the wet clay layer of a few cm thick, such force cannot but produce some increase of the S_F area, - little as it may be at the beginning. And at the next connections with increased S_F the tearing off force will inevitably be greater than before too, which in turn will bring about the next increase of the scaling off area and so on. It is obvious, that with a time and the increasing depth of the well the area S_F cannot, but constantly increase. In terms of automation theory the process considered is a one with a positive back feed, when a consequence increases its cause, which again increases the consequence.

It was mentioned above, that along with the tearing off force F_T there also exist forces, retaining the sector 5 in its place. They are the forces, that connect the scaling off sector 5 with neighboring sectors of the wet layer. Those forces are acting along the free surface's S_F perimeter - which is like a horse shoe, one side of the perimeter being the crack 4. With increasing the free surface's linear dimensions both force F_T and retaining forces are growing. However dependency of perimeter on the linear dimension of a surface is a linear one, while that of area is quadratic, which means that the force F_T is growing quicker, than the retaining forces are. So however little may be the force F_T as compared with the retaining forces at the beginning of the scaling off process, the moment will inevitably come, when that relationship would change to the opposite, and after certain amount of connections all links of the segment 5 with neighboring segments shall be broken and that segment shall collapse under its own weight.

The way to elimination of F_T force is in rejecting the mud pipe stopping before performing connections. The circulation is to be ceased by way of switching the pump's output from the well to a sedimentation tank. Thus, instead of instantaneous disappearance, the dynamic component p_{HD} of the well pressure should be continuously, during some minutes, brought down from its working value to zero. Continuous lowering of p_{HD} can be represented as a lowering by an infinitude of infinitesimal steps dp_{HD} . In the crack

4 corresponding pressure lowerings will be delayed, originating an infinitesimal tearing-off forces dF_T. According to their definition such forces can be neglected. An only condition is, that time periods between the steps are long enough, - so, that every consecutive step does not take place earlier, than the dF_T of the preceding step disappears. That condition is satisfied, if the switching the pump's output is performed slowly.

In the above example the computer model evaluated some parameters of caving generating process, that develops under conditions of a "clean" well, where caving has not yet occurred earlier. If it has, then the situation is essentially different. The caves in the well bore become accumulators of the drilling cuttings, whose particles fall out there, because of a sharp decrease of the ascending flow velocity. When accumulating, the cuttings mass gradually consolidates and under its weight sinks down till it gets stuck at some narrower intervals of the well bore, forming plugs. The plugs obstruct the ascending flow of the flushing liquid and bring about a sharp increase of p_{HD}.

In particular, under conditions, similar to those, used for the above computer model assessment, and with the same reference data, but with the well bore, obstructed by clay plugs, it was observed, that the pressure on the mud pump manometer was rising up to 2 MPa and more. So as compared to the clean well - see the computer model outputs - changes as follows took place:

- The difference of manometer pressure Δp_M = 2 - 0,85 = 1,15 MPa.
- The difference of hydrodynamic pressure p_{HD} = 0,27 + 1,15 = 1,42 MPa.

Increase of p_M could occur only on account of ascending flow, the one, blocked with the plugs. Thus the hydrodynamic pressure p_{HD} has risen by the factor of 1.42/ 0.27= 5.3. According to formula (7) the tearing off-force is to grow in the same proportion and, for the same free area S_F = 0,0001 m^2 , become F_T = 27*5.3 = 143 H. It is clear that caving and plugging intensely accelerate the process of their own generation.

A powerful impetus for collapsing the well bore walls is provided by the swabbing effect, caused by the drill string (and especially its bottom part - the drill collar) rising through a tightly fitting clay plug. For eliminating the swabbing effect while performing connections or other manipulations, including working up the drill pipe, the upward motion should be performed slowly and without stopping rotation and cessation of circulation (in case of connections rotation and circulation can be stopped only at the highest point of rising).

Extracting the drill string out of the well should also be performed at a smallest speed possible. Before beginning the extraction the well should be thoroughly flushed with periodical rotating. The flushing should be terminated no sooner, then readings of manometer have come down to the level, which is under existing conditions typical for the clean well.

Above, along with other geological factors, causing caving, presence in the clay massive of other rocks was pointed out. By caliper logging it was established, that particularly often big caves are arising at the contact of clays with formations of high solidity, such as siliceous gypsum, which has found wide occurrence in geological structures of south Kazakhstan. At contact with those rocks the well bore diameters often exceed 0.4 m - maximum the calipers can register. Scheme of the processes, arising in the described situation, the fig. 3 offers.

It was observed earlier, that in the course of bulging the wet layer of clay tends to increase its length. Extending of any segment of the wet layer is obstructed by neighboring segments of the same clay. However the lowest segment, that is in contact with the hard rock makes an exception. The part 5 of its annular butt-end is in contact with hard rock. The force F_R of resistance to extending is acting here.

However in the remaining part 6 of that butt that force is absent. As a result the force F_R and the causing extension force F_{EX} form a

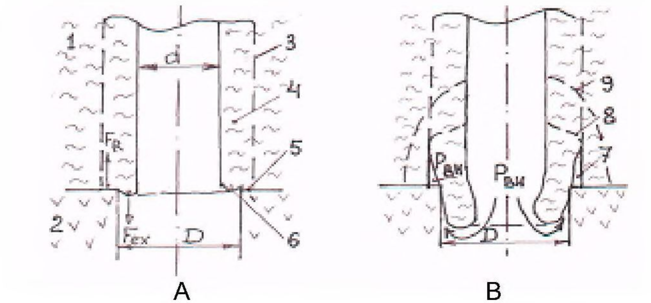


Fig. 3. Performance of the bulging clay at a contact with solid rock: A – initial stage of bulging; B – the following stage; 1 – clay; 2 – solid rock; 3 – border with the dry massive; 4 – wet layer; 5 – contacting part of the wet layer's butt; 6 – its free part; 7 – crack; 8 – border of the 1-st caving; 9 – border of the 2-d caving; D – drill bit diameter; d – well bore diameter in the bulging clay; F_R – resisting force, F_{EX} – extending force; p_{BH} - bore hole pressure

couple, tending to slew the contacting segment of the wet layer around the ledge of the hard rock clockwise (as on the fig 3). While performing that, the part 5 is torn off the hard rock contact surface, forming a crack 7; and the bottom segment of the wet layer creeps over the hard rock ledge and becomes suspended in the well bore. The pressure p_{BH} along the annular space between the well bore wall and the suspended segment of the wet layer penetrates into the crack 7, equalizing pressure at both sides of the segment. The pressure equalizing provides conditions for total separation of the lower segment of the wet layer and for its eventual collapse.

The chances of collapsing in this last situation are higher than in those considered earlier. Thus a crack 3 (fig. 2) in the wet layer can be larger or smaller and have different degrees of openness. Often it is situated at only one side of the well bore. Readiness for collapsing requires, that the crack should be growing till the needed stage of scaling off is achieved, which can be effected only after certain number of connections and drilling several dozens of meters.

On the latter occasion the entire lower segment of the wet bulging annular layer, extending, creeps over the ledge of the hard rock, forming above the ledge a circular crack 7. Thus in a short time, - depending on the clay's bulging speed only -, a segment of relatively big mass gets prepared to collapsing.

Separation of a large volume of clay from the well bore results in breach of a balance, that existed before. At the roof 8 of the cave which has became foot of the wet layer, the obstacles to its extending are absent. That brings about a further extension, causing some new cracks of displacement, coming into being at the border of the dry massive and the wet layer. There the drilling mud penetrates, bringing along p_{BH} pressure and equalizing pressure on both sides of an another segment, making it free and ready to a next collapsing, after which the cave, instead of the "old" roof 8, would obtain a new one 9. Along with growing upwards the cave also increases its width, because through the cracks, separating it from the wet layer, the dry massive absorbs water and thus forms new wet layers at greater distance from one another. The collapse of the cave's roof will be followed with that of its walls.

Conclusions

1. Drilling wells at uranium deposits of South Kazakhstan is aggravated with easily dispersed clays which prevail in the geological structure of the region.
2. Absence of confining pressure in the well bore zone brings about opening cracks and saturating that zone with water of drilling mud.
3. Growth of hydrate envelops on the structural lamellae of clays causes bulging of the well bore zone and building up stresses there
4. In weakened segments of the wet layer a longitudinal cracks of displacement appear, equalizing pressure on both sides of that layer.
5. At circulation cessation pressure in cracks for some time period remains higher than in the well bore, which develops in the wet layer the process of scaling off.

6. To prevent this the circulation cessation should be effected continuously by gradual switching the pump's output from the well to a sedimentation tank.

7. An impetus to wet layer's collapsing provides a swabbing effect, arising while pulling the drill pipe up through clay plugs.

8. While drill pipe reciprocating or making connections the rotation and circulation should not be stopped, at least till the required height is reached.

9. Well flushing before the drill string extraction should be preformed with the drill string rotation on, and as long, as the pressure has not come back to norm.

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