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АКАДЕМИЯСЫ» РҚБ

«ҚАЗАҚСТАН РЕСПУБЛИКАСЫ
ҰЛТТЫҚ ҒЫЛЫМ АКАДЕМИЯСЫ» РҚБ

# ХАБАРЛАРЫ

# ИЗВЕСТИЯ

РОО «НАЦИОНАЛЬНОЙ
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**B.T. Ratov[1], V.L. Khomenko[2], Z.G. Utepov[3*], Ye.A. Koroviaka[2], A.A. Seidaliyev[3], 2025.**
[1]Kazakh National Research Technical University named after K.I. Satpayev, Almaty, Kazakhstan;
[2]Dnipro University of Technology, Dnipro, Ukraine;
[3]Caspian State University of Technology and Engineering named after Sh. Yesenov, Aktau, Kazakhstan.
E-mail: otepzaman@gmail.com

# BLADE BIT DRILLING IN KAZAKHSTAN: ACHIEVED RESULTS, UNRESOLVED ISSUES

**Ratov Boranbay Tovbasarovich** – Doctor of Technical Sciences, Professor, Head of the Department "Geophysics and Seismology", Kazakh National Research Technical University named after K.I. Satpayev, Almaty, Kazakhstan, E-mail: b.ratov@satbayev.university, https://orcid.org/0000-0003-4707-3322;
**Khomenko Volodymyr Lvovych** – Candidate of Technical Sciences, Associate Professor of the Department "Oil and Gas Engineering and Drilling", Dnipro University of Technology, Dnipro, Ukraine, E-mail: inteldriller@gmail.com, https://orcid.org/0000-0002-3607-5106;
**Utepov Zamanbek Gabitovich** – Master of engineering and technology, PhD student of the Department "Ecology and Geology", Caspian State University of Technology and Engineering named after Sh. Yessenov, Aktau, Kazakhstan, E-mail: otepzaman@gmail.com, https://orcid.org/0009-0000-5086-7698;
**Koroviaka Yevhenii Anatoliiovych** – Candidate of Technical Sciences, Head of the Department "Oil and Gas Engineering and Drilling", Dnipro University of Technology, Dnipro, Ukraine, E-mail: koroviaka.ye.a@nmu.one, https://orcid.org/0000-0002-2675-6610;
**Seidaliyev Askar Abiyevich –** Candidate of Technical Sciences, Associate Professor of the Department "Petrochemical Engineering", Engineering Faculty, Caspian University of Technology and Engineering named after Sh. Yessenov, Aktau, Kazakhstan, E-mail: askar.seidaliyev@yu.edu.kz, https://orcid.org/0000-0002-5346-3004.

**Abstract:** Blade bits reinforced with carbide cutters and Polycrystalline Diamond Compact (PDC) cutters are widely used in geotechnological and oil and gas wells, including Kazakhstan. Combined drilling techniques are economically advantageous: carbide-reinforced bits are used for softer rocks, while PDC-reinforced bits handle harder formations. The efficiency of PDC bits depends on the interaction between individual cutters and the rock, making it critical to understand these patterns to improve performance and durability.

This study employs system analysis of models describing cutter-rock interactions,

focusing on the actual contact area and the cutter's inclination angle. The research models the interaction area as a circle segment and incorporates a negative cutter inclination angle. Results reveal the phenomenon of bit "hanging" in formations of alternating hardness, confirmed through theoretical and experimental approaches.

A bladed spud bit with no cutters in the near-axis region was developed, relying on drilling fluid or core breakers to remove rock pillars. Industrial tests showed a 10-15% increase in drilling productivity and a 1.5-fold increase in tool life. Additionally, a formula for calculating the penetration depth of a single PDC cutter was derived, enabling predictions of initial drilling speeds. These results offer practical solutions for optimizing PDC bits in challenging drilling conditions.

**Keywords:** well drilling, bladed bit, "hanging", deepening, PDC cutter.

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**Б.Т. Ратов[1], В.Л. Хоменко[2], З.Г. Утепов[3*], Е.А. Коровяка[2], А.А. Сейдалиев[3], 2025.**

[1]ЕҚҚ «Қ.И. Сәтбаев атындағы Қазақ ұлттық техникалық зерттеу университеті», Алматы, Қазақстан;

[2]Ұлттық техникалық университет «Днепр политехникасы», Днепр, Украина;

[3]Ш. Есенова атындағы Каспий мемлекеттік технологиялар және инжиниринг университеті, Ақтау, Қазақстан.

E-mail: otepzaman@gmail.com

## ҚАЗАҚСТАНДА ҚАЛАҚШАЛЫ ҚАШАУЛАРМЕН ҰҢҒЫМАЛАРДЫ БҰРҒЫЛАУ: ҚОЛ ЖЕТКІЗІЛГЕН НӘТИЖЕЛЕР, ШЕШІЛМЕГЕН МӘСЕЛЕЛЕР

**Ратов Боранбай** – Техника ғылымдарының докторы, профессор, «Геофизика және сейсмология» кафедрасының меңгерушісі, Қ.И. Сәтбаев атындағы Қазақ ұлттық техникалық зерттеу университеті, Алматы, Қазақстан, E-mail: b.ratov@satbayev.university, https://orcid.org/0000-0003-4707-3322;

**Хоменко Владимир** – Техника ғылымдарының кандидаты, «Мұнай-газ инженериясы және бұрғылау» кафедрасының доценті, Днепр технологиялық университеті, Днепр, Украина, E-mail: inteldriller@gmail.com, https://orcid.org/0000-0002-3607-5106;

**Утепов Заманбек** - Техника және технология магистрі, «Экология және Геология» кафедрасының PhD докторанты, Ш. Есенов атындағы Каспий технологиялық және инженерлік университеті, Ақтау, Қазақстан, E-mail: otepzaman@gmail.com, https://orcid.org/0009-0000-5086-7698;

**Коровяка Евгений** - Техника ғылымдарының кандидаты, «Мұнай-газ инженериясы және бұрғылау» кафедрасының меңгерушісі, Днепр технологиялық университеті, Днепр, Украина, E-mail: koroviaka.ye.a@nmu.one, https://orcid.org/0000-0002-2675-6610;

**Сейдалиев Аскар** - Техника ғылымдарының кандидаты, «Мұнай-химия инженериясы» кафедрасының доценті, Ш. Есенов атындағы Каспий технологиялық және инженерлік университеті, инженерлік факультеті, Ақтау, Қазақстан, E-mail: askar.seidaliyev@yu.edu.kz, https://orcid.org/0000-0002-5346-3004.

**Аннотация:** Поликристалды алмаздан (PDC) жасалған карбидті кескіштермен және кескіштермен нығайтылған қалақшалы қашаулар Қазақстанды қоса алғанда, геотехнологиялық, Мұнай және газ ұңғымаларын салуда кеңінен қолданылады. Бұрғылаудың аралас әдістерін қолдану үнемді: карбидті кескіш қашаулар жұмсақ тау жыныстары үшін, ал PDC кескіштері қатты тау жыныстары үшін қолданылады. PDC қашауының тиімділігі жеке азу тістердің жыныспен өзара әрекеттесуімен анықталады, бұл құралдың өнімділігі мен беріктігін жақсарту үшін осы заңдылықтарды зерттеуді маңызды етеді. Осы зерттеу аясында инсектордың нақты жанасу аймағына және инсектордың көлбеу бұрышына баса назар аудара отырып, инсектордың жыныспен өзара әрекеттесу модельдеріне жүйелі талдау жүргізілді. Шеңбер сегменті және кескіштің теріс бұрышы түріндегі жанасу аймағын ескере отырып, өзара әрекеттесу модельденген. Нәтижелер теориялық және эксперименттік түрде расталған айнымалы қаттылық жыныстарының қиылысында қашаудың «қатып қалу» құбылысын анықтады. Орталық айналу аймағында кескішсіз пышақ қашау жасалды, мұнда жынысты кетіру жуу сұйықтығы немесе ядро жойғыштары арқылы жүзеге асырылады. Өнеркәсіптік сынақтар бұрғылау өнімділігінің 10-15% - ға және қашаудың қызмет ету мерзімінің 1,5 есе артқанын көрсетті. Сонымен қатар, бұрғылаудың бастапқы жылдамдығын болжауға мүмкіндік беретін бір PDC кескіштің ену тереңдігін есептеу формуласы шығарылды. Нәтижелер күрделі геологиялық жағдайларда PDC қашауларын оңтайландырудың практикалық шешімдерін ұсынады.

**Түйін сөздер:** Ұңғымаларды бұрғылау, қалақшалы қашау, «қатып қалу», тереңдеу, PDC кескіш.

**Б.Т. Ратов[1], В.Л. Хоменко[2], З.Г. Утепов[3*], Е.А. Коровяка[2], А.А. Сейдалиев[3], 2025.**

[1]НАО «Казахский Национальный исследовательский технический университет им. К.И. Сатпаева», Алматы, Казахстан;

[2]Национальный технический университет «Днепровская политехника», Днепр, Украина;

[3]Каспийский государственный университет технологий и инжиниринга им. Ш. Есенова, Актау, Казахстан.

E-mail: otepzaman@gmail.com

## БУРЕНИЕ СКВАЖИН ЛОПАСТНЫМИ ДОЛОТАМИ В КАЗАХСТАНЕ: ДОСТИГНУТЫЕ РЕЗУЛЬТАТЫ, НЕРЕШЕННЫЕ ПРОБЛЕМЫ

**Ратов Боранбай Товбасарович** – доктор технических наук, профессор, заведующий кафедрой «Геофизика и сейсмология», Казахский Национальный исследовательский технический университет им. К.И. Сатпаева, Алматы, Казахстан, E-mail: b.ratov@satbayev.university, https://orcid.org/0000-0003-4707-3322;

**Хоменко Владимир Львович** – кандидат технических наук, доцент кафедры «Нефтегазовая

инженерия и бурение скважин», Днепровский технологический университет, Днепр, E-mail: inteldriller@gmail.com, https://orcid.org/0000-0002-3607-5106;
**Утепов Заманбек Габитович** – магистр техники и технологий, PhD докторант кафедры «Экология и геология», «Каспийский Университет технологий и инжиниринга им. Ш. Есенова, Актау, Казахстан, E-mail: otepzaman@gmail.com, https://orcid.org/0009-0000-5086-7698;
**Коровяка Евгений Анатольевич** – кандидат технических наук, заведующий кафедрой «Нефтегазовая инженерия и бурение», Днепровский технологический университет, Днепр, Украина, E-mail: koroviaka.ye.a@nmu.one, https://orcid.org/0000-0002-2675-6610;
**Сейдалиев Аскар Абиевич** – кандидат технических наук, доцент кафедры «Нефтехимическая инженерия» инженерный факультет, Каспийский Университет технологий и инжиниринга им. Ш. Есенова, Актау, Казахстан, E-mail: askar.seidaliyev@yu.edu.kz, https://orcid.org/0000-0002-5346-3004.

**Аннотация.** Лопастные долота, армированные твердосплавными резцами и резцами из поликристаллического алмаза (PDC), широко применяются при строительстве геотехнологических, нефтяных и газовых скважин, включая Казахстан. Экономически выгодным является использование комбинированных методов бурения: долота с твердосплавными резцами применяются для мягких пород, а с PDC-резцами – для твердых. Эффективность PDC-долота определяется взаимодействием отдельных резцов с породой, что делает исследование этих закономерностей важным для повышения производительности и долговечности инструмента.

В рамках данного исследования проведен системный анализ моделей взаимодействия резца с породой, с акцентом на фактическую площадь контакта и угол наклона резца. Было смоделировано взаимодействие с учетом площади контакта в виде сегмента окружности и отрицательного угла наклона резца. Результаты выявили феномен «зависания» долота при пересечении пород переменной твердости, что подтвердилось теоретически и экспериментально.

Разработано лопастное долото без резцов в центральной зоне вращения, где удаление породы осуществляется с помощью промывочной жидкости или разрушителей керна. Промышленные испытания показали увеличение производительности бурения на 10-15% и увеличение срока службы долота в 1,5 раза. Дополнительно выведена формула для расчета глубины проникновения одного PDC-резца, что позволяет прогнозировать начальные скорости бурения. Полученные результаты предоставляют практические решения для оптимизации PDC-долот в сложных геологических условиях.

**Ключевые слова:** бурение скважин, лопастное долото, «зависание», углубление, резец PDC

**Introduction.** In Kazakhstan, the drilling of wells is expanding rapidly, employing bladed bits featuring tungsten carbide and PDC cutters. This has led to a noticeable decline in the effective usage of roller cone bits. Blade bits are particularly prevalent in the creation of technological wells for uranium mining and in the drilling of oil and gas wells. Additionally, this type of rock-cutting tool is extensively utilized in the drilling of water wells.

The extensive drilling of technological wells is driven by the necessity to harness the vast reserves of world-class uranium resources located in the southern region of Kazakhstan, associated with aquifers. These aquifers are situated at depths of up to 800-900 meters below the surface and are surrounded by soft layers (up to 300-350 meters) transitioning to intermittently hard rock formations (interlayers categorized as VII-VIII drillability) from 300-350 meters to the planned drilling depth (Togasheva, 2023). Kazakhstan ranks one of the first places in the world in the extraction of this type of raw material.

Such geological conditions determine, for economic reasons, the current use of combined drilling with blade bits:

– In the drilling of the upper segment of a geological section characterized by soft rocks, specialized peak-shaped blade bits (spud bit) equipped with conventional carbide cutters are utilized.

– For drilling rocks with varying hardness levels, interspersed with layers of medium-hard rocks, the process involves the use of «BIT» bits, essentially blade bits equipped with diamond-carbide PDC cutters.

Over the past decade, there has been a noticeable shift towards employing PDC bits, as opposed to roller cone bits, in the drilling of oil and gas wells within the oil fields of western Kazakhstan (Akhundov, 2023: 14). The adoption of PDC tools has demonstrated a substantial improvement in the key technical and economic parameters of drilling operations. For instance, in the drilling of production wells at the extensive Uzen oil field, the replacement of roller cone bits with PDC tools resulted in a remarkable increase in the initial rate of penetration (ROP) from 8-9 m/h to 17-18 m/h. At the same time, the tool life was increased from 600-700 m to 4,500-5,000 m of penetration (Borash, 2023).

The extensive use of blade bits and the imperative to improve them to solve emerging challenges determine the relevance of research in this field.

A single cutter of a PDC bit has a complex structure, and its impact on the rock varies depending on its shape and location. This variability influences both the efficiency of rock destruction and the durability of the cutter itself, consequently impacting the overall performance of the bit (Xiao, 2019; Zhang, 2023).

Hence, a crucial and pressing objective is to establish the patterns governing the interaction between the PDC bit's cutter and the well bottom. The outcomes of these investigations hold substantial practical value in the design of PDC bits tailored for diverse geological and technical conditions, as well as in optimizing drilling technology parameters.

Traditionally, to solve this problem, the approach involved considering the indentation of a sharpened prismatic cutter into the rock over an area resembling a rectangle (Biletsky, 2019: 7; Kozhevnykov, 2018: 8; Liu, 2020).

Nevertheless, the prevalent cutters feature a round cross-section and an inclination angle relative to the well bottom. Consequently, it becomes necessary to treat the contact area as a segment of a circle and consider the negative angle of the cutter inclination when determining the interaction patterns between the cutter

and the well bottom. This methodology for addressing the issue has enabled the derivation of a relevant formula for the ROP, factoring in the strength characteristics of the bottom rock, weight on bit (WOB), and the rotary speed of the tool.

The purpose of this study is to analyze the interaction dynamics between the cutter of PDC bits and the well bottom, considering both the circular shape and the negative inclination angle of the cutter in relation to the bottom and the actual interaction area in the «cutter-rock» pair is considered as a segment of a circle.

To accomplish this purpose, the following tasks were solved:

– Identify the maximum penetration depth of a single cutter on a PDC bit into the rock.

– Calculate the rate of penetration using a PDC bit while accounting for the specified factors.

**Materials and basic methods**

The object of study is the interaction characteristics of a single cutter on PDC bits with the rocks at the well bottom.

The study was based on the idea of considering the genuine interaction area within the «cutter-rock» pair as a circular segment, along with factoring in the negative angle of inclination of the cutter. This approach aimed to delineate the interaction patterns between the cutter and the well bottom.

To solve the problems, the following research methods were used.

A systematic analysis was conducted on models describing the interaction between the PDC cutter and the rock bottom of the well, as presented in the literature. In the initial phase of the research, a simplified model of the process was embraced. Despite its simplicity, this model enables the quantification of the impact of geometric parameters and the spatial orientation of the cutter concerning the well bottom on its penetration depth. To achieve this, a simplified theoretical research method was employed. The resulting formula derived from this approach proves versatile, applicable not only to more complex models considering factors such as vibrations and variable coefficients of friction but also amenable to experimental validation under real production conditions.

A systematic analysis explores the interaction between a single cutter of a PDC bit and the rock, taking into consideration the actual contact area in the «cutter-rock» pair and the inclination angle of the cutter.

**Results**

There are several challenges associated with using of PDC bits, inherent to rotary drilling tools:

1) Issues arise with the «hanging» of the bit when encountering layers of hard rock, leading to complications.

2) The development of a bit with design parameters that guarantee an optimal rate of destruction and the formation of the well is a complex task, considering the fundamental physical, mechanical, and geological characteristics of the rocks being drilled.

3) A notable decline in ROP and the durability of rock-cutting tools occurs with an escalation in the hardness and abrasiveness of rocks (Yang, 2020).

The first issue is common to all rotary drilling tools designed for cutting rock. It emerges as the tool approaches the axis of rotation, where its peripheral speed diminishes to zero. Consequently, there is a significant increase in axial static load on the cutters located in this region. In simpler terms, the rock undergoes compressive loading, and most rocks exhibit substantial resistance to failure under this specific deformation. Consequently, in order to penetrate a solid rock layer, the tool requires additional time to break it apart, resulting in the occurrence of the «hanging» phenomenon. Naturally, this impedes the normal progress of well penetration, ultimately diminishing the overall efficiency of drilling operations.

A similar phenomenon has been described abroad during the drilling of deep oil and gas wells using PDC bits (Dreus, 2016: 41). This occurrence has been noted in the drilling of technological wells, even in the upper segment of a geological section predominantly comprised of soft rocks, particularly when encountering harder interlayers of rocks. Typically, under such circumstances, a bladed spud bit developed by JSC Volkovgeologiya is used (Fig. 1) (Biletsky, 2019: 7).

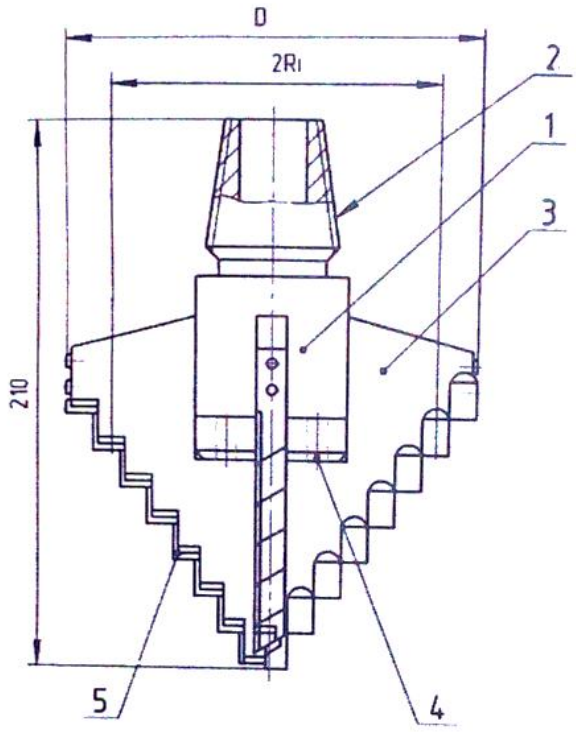


Fig. 1. Spud bit designed by JSC Volkovgeologiya

1 – bit body, 2 – thread for connection with the drill string, 3 – blades, 4 – jet nozzles, 5 – cutters

Long-term practice of its use has shown that its durability is on average 280 m. Upon visual inspection of the tool post-use, it becomes evident that the maximum wear occurs in the region near the axis of the tool.

Regarding the second issue, numerous patents exist, and their implementation, at most, addresses specific challenges aimed at enhancing drilling efficiency and prolonging bit life. Nevertheless, a tool has yet to be developed with design parameters that comprehensively consider the entire array of fundamental physical and geological properties of rocks.

This set of challenges encompasses issues such as the absence of an efficient bit capable of drilling a technologically viable well in a single trip to the full depth, ranging from zero to 700-800 m. This consideration is crucial, especially given the fact that the lower part of the geological section consists of rocks with significantly lower drillability compared to the upper part.

Additionally, these challenges encompass the lack of initial theoretical investigations into the impact of the configuration of the diamond-carbide cutter PDC and its spatial orientation relative to the well bottom on the individual penetration depth of the cutter into the rock. Despite long-standing studies on the introduction of a prismatic cutter, similar studies for diamond-carbide cutters are notably absent. Obtaining such insights would enable the calculation of the initial expected ROP based on the rock hardness, drilling mode parameters, and the geometry of the PDC cutter.

The third issue is connected to the noticeable decline in the Rate of Penetration (ROP) and the life of the tool as the hardness and abrasiveness of rocks increase. If we employ the established XII-point drillability scale to assess the ROP while considering the mentioned properties, it becomes apparent that in rocks categorized as V, the ROP is approximately 3.5 m/h. However, in rocks falling under category XII (characterized as the hardest abrasive rocks), this figure plummets to 0.2 m/h, marking a substantial reduction of 17 times (Ratov, 2023: 10).

To solve these three issues, a comprehensive set of methods was employed, encompassing both theoretical and experimental research, developmental work, and production tests for the created tools.

The first issue has been effectively addressed through theoretical and practical research conducted by scholars from the Kazakh National Research Technical University, named after K.I. Satpayev (Satbayev University) in various scientific articles and patents of the Republic of Kazakhstan (Biletsky, 2019: 7; Ratov, 2020: 6; Ratov, 2022).

As a result of the research, the phenomenon of bit "hanging" was theoretically substantiated (Ratov, 2020: 6). This work shows that when a rotating blade bit encounters the bottom hole, the axial load undergoes redistribution among the cutters positioned on the blade according to a specific relationship:

$$Q_i = h\left(\frac{E\delta\gamma}{4\pi((i)-0.5)(1-\mu^2)}+\frac{Df}{2K}\right),$$

where h is the depth of the rock layer removed per revolution of the bit.

$$h = \frac{ROP}{nm}, \quad (2)$$

*ROP* is rate of penetration;

*n* is bit rotary speed;

*m* is number of cutters deepening the bottom of the well;

*E* is Young's modulus;

$\delta$ is width of the cutter;

*i* is number of the cutter in the direction from the axis of rotation of the spud bit to its outer diameter;

$\gamma$ is coefficient taking into account the cramped conditions of the cutters when working in a well, we take $\gamma = 1.38$ (Ihnatov, 2022);

$\mu$ is Poisson's ratio of the rock;

*D* is well diameter;

*f* is coefficient of friction at the "cutter-rock" boundary;

*K* is amount of cutters *i*, counting from the axis of rotation of the bit.

Analysis of formula (1) shows that the first term in brackets depends on the position of the cutter on the blade, i.e. on the radius $R_i$ of its rotation, and the second term does not depend on $R_i$.

Calculations conducted following the methodology outlined in the article (Ratov, 2020: 6) indicate that the axial load on each blade of the bit is minimized at the periphery of the blade adjacent to the well wall. Conversely, in the region near the axial axis of rotation, the axial load attains a substantial magnitude, escalating by 8-10 times. This phenomenon is attributed to the circular movement of different sections of the blades, with their lengths being proportional to the radius of rotation. The cutters in the near-wall region of the well cover a maximum path, while the path reduces to zero at the axis of rotation. As a unified bit blade is considered, the depth of the well penetrated by the blade cutters remains the same regardless of their placement. This uniformity is maintained through the redistribution of the effective WOB, which increases toward the tool axis, compensating for the reduction in the path of the cutters. Consequently, the spud bit experiences a halt or «hanging,» particularly when encountering solid layers. Consequently, the tool requires additional time to disintegrate the central section of the well bottom. This complication in the drilling process results in diminished technical and economic performance indicators.

To alleviate the excessive load in the near-axis region of the bit's rotation, a straightforward solution involves eliminating the near-axis segments of the blades equipped with cutters. The resulting core can be cleared away using a stream of drilling fluid or a mechanical core breaker. This design approach serves to decrease the overall load on the wellbore bottom, reduce the energy consumption of the process, and enhance the durability of the pointed bit.

Researchers from Satbayev University developed and tested various designs of bladed spud bits based on this principle. The most efficient among them was the patented spud bit PC (Fig. 2), created according to the specifications in patent (Ratov, 2022).

Spud bit PC (Fig. 2) contains a tubular housing 1 with a thread 2 for connection to the drill string (not shown). Four stepped blades 3 are welded to the body, tapering towards the well bottom. Each stage of the blade is equipped with lamellar carbide cutters 4. The upper largest part of the blades is equipped with calibrating cutters 5, and their rear part is equipped with emergency carbide cutters 6. The lower cantilever part of the stepped blades is welded to the ring 7, with sealed carbide cutters 8, to increase the rigidity of the structure. As follows from Fig. 2, the edge of the cutters 9 of the lower stage of the blades is located from the tool axis at a distance of 35:2 = 17.5 mm. This makes it possible to remove the load from the axial area of the spud bit, which is formed during the rotation of the blades of the target rock or is washed away by the washing liquid (in soft rocks) (Dudlia, 2018: 10) or destroyed by the cutters 8 of the stiffening rings 7.

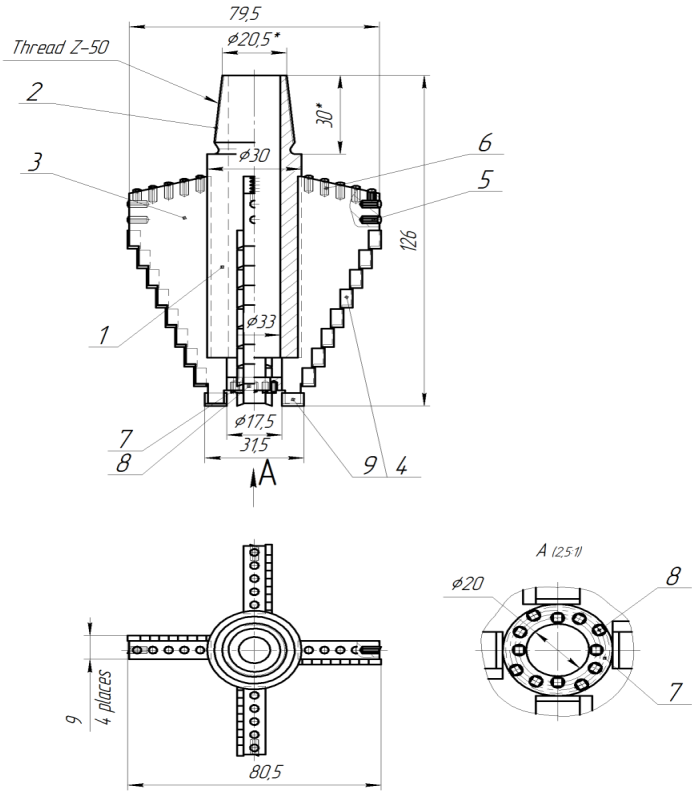


Fig. 2. Blade spud bit of PC type.
1 – tubular housing; 2 – thread; 3 – stepped blade; 4 – carbide cutters; 5 – calibrating cutters; 6 – emergency carbide weapons; 7 – stiffening ring; 8 – cutters of the stiffening ring; 9 – end cutters

Drilling through the dense clays in the lowest interval led to a more significant reduction in speed, slowing down to 3 m/h. The increase in WOB caused the lower incisors to deform and halt the drilling process. Subsequently, the remaining section (430-650 m) was drilled using a blade bit equipped with PDC cutters. Following production tests, a novel combined drilling tool was proposed and subsequently patented (Ratov, 2022). The key distinction from existing tools lies in the termination of the body, featuring blades, with a small-diameter core bit at the bottom. The new tool integrates the armament and blades, employing a mix of carbide cutters and PDC cutters in alternating fashion. Notably, the carbide cutter edges are positioned above the placement plane of the PDC cutters by a specific amount Δ, as defined by:

$$\Delta = (b_{\text{f}} - b_i)\cos\alpha \qquad (3)$$

where $b_{\text{f}}$ is final blunting of the cutters after drilling the upper interval composed of soft rocks;

$b_i$ is initial blunting of the incisors;

α is angle of sharpening of the carbide cutter.

Drafts of a unified spud bit have been developed, and post-production, the tool will undergo testing in real operational conditions.

To address concerns regarding the second issue, extensive research has been conducted (Dong, 2018; Huang, 2017; Tian, 2022), exploring various aspects of the interaction between PDC bit cutters and rock. This encompasses investigations into the impact of load redistribution beneath the bit, the influence of friction forces on the ROP, the effect of the bottom hole shape on its efficiency in rock destruction, modeling the PDC cutter for cutting depth, modes, specific energy, and the development of diverse drillability models considering the destruction of rocks with varying properties. Notably, all these studies failed to delve into matters associated with the utilization of round cutters and their negative angle of inclination towards the bottom of the well. Meanwhile, it's important to highlight that significant attention has been directed towards examining the interaction of prismatic carbide cutters with sharpening (Biletsky, 2019: 7; Kozhevnykov, 2018: 8; Liu, 2020).

Therefore, a crucial objective is to determine how the round configuration of the PDC cutter and its spatial positioning relative to the bottom of the well affect the penetration depth into the rock, considering both the strength of the rock and the external loads applied to the cutter.

For this purpose, an initial stage involves employing a cost-effective theoretical research method. Despite its affordability, this method enables us to roughly estimate the impact of the mentioned loads and the response of the rock mass on the cutter's penetration depth.

Considering the aforementioned, the theoretical method involves the following assumptions and simplifications:

– The rock is treated as an isotropic medium, possessing identical physical and mechanical characteristics in all directions.

– The coefficient of friction between the cutter and the rock is presumed to be consistent across all points on the bottom.

– Rotary speed and WOB are assumed to remain constant over time.

If the outcome proves positive, the established relationships can be applied to address issues involving more intricate models and validated in practical production settings. The comprehensive process diagram is illustrated in Figure 3. The PDC cutter is propelled into the rock by the force $P_0$. As it advances, a thin layer of rock is extracted, equivalent to the depth of the cutter recess. In practice, the movement follows a spiral pattern; nevertheless, this assumption is justified by the minimal vertical displacement of the cutter. This enables the derivation of an engineering calculation-level result – an equation for the ROP in rotary drilling, contingent on the technological parameters of drilling and the rock's strength properties.

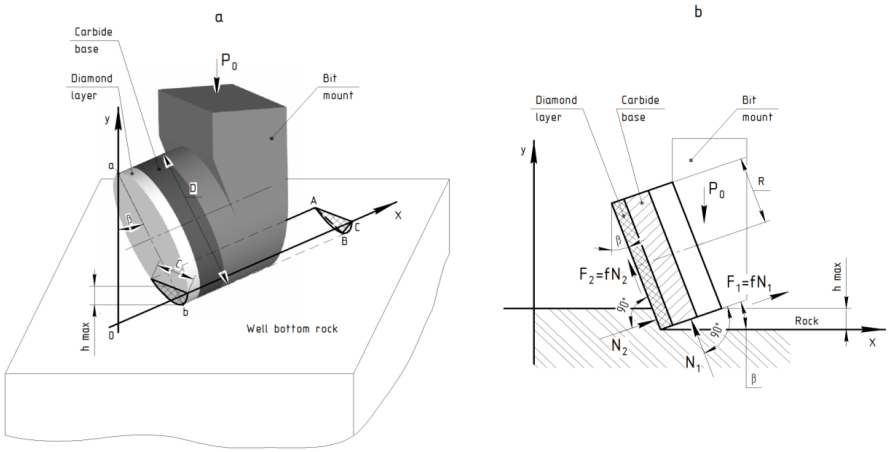


Fig. 3. Schematic diagram of rock destruction by a PDC cutter
a is the interaction of the PDC cutter with the rock, b is the forces acting on the working element of the PDC cutter

Fig. 3 also indicates that the indentation in the rock takes on the configuration of a groove mirroring the shape of the diamond-containing layer of the PDC cutter. This groove resembles a segment of a circle with a height $h_{max}$ and chord C. The leading diamond-containing edge of the PDC cutter consistently maintains an inclination relative to the vertical, marked by an angle $\beta$ (Fig. 3). This inclination is deliberate to enhance the strength of the diamond layer when experiencing the reaction from the bottom.

Let's analyze the equilibrium of the applied forces by projecting them onto the X axis (Fig. 3b):

$$\sum \bar{x} = 0;\ \ N_2 \cos\beta - fN_2 \cos(90° - \beta) - N_1 \cos\beta - N_1 \cos(90° - \beta) = 0, \quad (4)$$

Let us consider the equilibrium of the acting forces when projecting onto the Y axis (Fig. 3b).

$$\sum \bar{y} = 0; N_2 \cos(90° - \beta) + N \cos\beta + fN_1 \cos(90° - \beta) + N_1 \cos\beta - P_0 = 0. \quad (5)$$

After solving and transforming equations (4) and (5), we determine the force $P_0$:

$$P_0 = \frac{\cos 2\beta(1+f)}{f\cos\beta - \sin\beta} N_2. \quad (6)$$

The normal $N_2$ reaction can be expressed by the following formula:

$$N_2 = H_c \sin\beta F_c, \quad (7)$$

where $H_c$ – contact strength of rock: $H_c = 0.69P_S$;

$P_S$ is rock hardness according to L.A. Schreiner (Sudakov, 2018);

$F_c$ is area of part of the PDC plate pressed into the bottom (Fig. 3a).

When considering the equilibrium of forces acting on the embedded diamond-carbide PDC cutter, the following equation was obtained:

$$P_0 \frac{(\cos\beta - \sin\beta)}{\sin(2\beta)(1+f^2)} = H_c sin\beta F_c = H_c sin\beta \times 0.5[rl - C(r - h_{max})], \quad (8)$$

where $F_c = 0.5[rl - C(r - h_{max})]$;

$r$ is radius of the PDC plate;

$l$ is the length of the arc of the segment pressed into the bottom;

$C$ is segment chord length (Fig. 3, a);

$h_{max}$ is the height of the segment (Fig. 3, a).

Having solved (8) for $h_{max}$ and carried out the necessary transformations, we obtain:

$$h_{max} = P_0 \frac{(\cos\beta - \sin\beta)}{C \cdot \sin 2\beta(1+f^2)H_K \sin\beta} - \left(\frac{rl}{C} - r\right). \quad (9)$$

However, utilizing the resulting formula (9) poses challenges in practical applications, as its output (the value $h_{max}$ representing the segment's height) is adversely influenced by other parameters (r, l, C) in the second term associated with $h_{max}$. Acknowledging these challenges, we introduce an approximate dependence (6) that allows for practical use in calculations.

To achieve this, we substitute the PDC cutter segment (Fig. 3, a), penetrating the rock to a depth of $h_{max}$, with an isosceles triangle embedded at the same depth, having a base equal to the length of the chord C. It has been observed that at shallow depths h, the triangle's area decreases by approximately 20-25% compared to the segment area. In other words, if we denote the segment and isosceles triangle areas as S1

and S2, respectively, their ratio is approximately S1:S2 = 1.2-1.25. Approximately replacing the segment's area with that of the mentioned triangle, we obtain:

$$\frac{P_o(\cos\beta-\sin\beta)}{\cos(2\beta 1+f^2)}=0.62P_s\sin\beta\frac{Ch_{\max}}{2}. \quad (10)$$

From dependence (7) we find the penetration depth $h_{max}$ of the PDC cutter:

$$h_{\max}=\frac{2P_o(\cos\beta-\sin\beta)}{C\cdot 0.62P_s\sin\beta\cos(2\beta)(1+f^2)} \quad (11)$$

The height of a circle segment $h_{max}$ can also be expressed through its chord C and the radius of the cutter r as follows

$$h_{\max}=r-\sqrt{r^2-\frac{C^2}{4}} \quad (12)$$

By setting equations (8) and (9) equal to each other and solving them simultaneously, we can find the chord C's value for the PDC cutter penetration segment into the rock during well drilling. Once the chord C is determined, the height of the circular segment, $h_{max}$, corresponding to the depth of the PDC cutter into the rock, can be calculated using either formula (11) or (12).

It's worth noting that calculating the value of the chord C presents a complex analytical challenge, yet it can be readily addressed using suitable software such as Excel, Mathcad, etc. or through graphical methods.

In line with the chosen process model for rotary drilling, the initial ROP for bottom well penetration is determined by the following formula (Biletsky, 2019: 7):

$$ROP=h{\cdot}m{\cdot}n,\ m/min \quad (13)$$

where *h* is the deepening of the bottom per one revolution of the tool by cutters located on the same radius of rotation;

*m* is number of cutters deepening the bottom of the well;

*n* is tool rotary speed, rpm.

Let's illustrate the procedure for determining the penetration depth of a PDC cutter per revolution with a specific example.

Initial data: weight on bit WOB = 60 kN, number of cutters at the end of the bit $m_0$ = 25, and at one radius of rotation m = 4; PDC cutter diameter is 13 mm, then r = 6.5 mm; rotary speed n = 120 rpm; front angle of inclination of the front edge β = 15º; rock hardness according to A.A. Schreiner $P_s$ = 4 kN/mm$^2$; f=0.3.

Solution:

The load on one PDC cutter will be

$$P_c = \frac{WOB}{m} = \frac{60}{25} = 2.4 \text{ kN.}$$

Presenting formula (8) in the form

$$h_{\max} = \frac{k}{C},$$

where $k$ is the result of calculations with constant values included in formula (11)

$$k = \frac{2P_c(\cos\beta - \sin\beta)}{0.62P_s \sin\beta\cos(2\beta)(1+f^2)}$$

Then we determine $k$ by substituting all known quantities

$$k = \frac{2 \cdot 2.4 \cdot (\cos 15 - \sin 15)}{0.62 \cdot 4 \cdot \sin 15 \cos(2 \cdot 15)(1+0.4^2)} = 5.263 \text{ mm}^2.$$

Thus, we compile a system of equations (8) and (9) for the given conditions

$$\begin{cases} h_{\max} = \dfrac{k}{C} \\ h_{\max} = r - \sqrt{r^2 - \dfrac{C^2}{4}} \end{cases} \rightarrow \begin{cases} h_{\max} = \dfrac{5.263}{C} \\ h_{\max} = 6.5 - \sqrt{6.5^2 - \dfrac{C^2}{4}} \end{cases} \quad (14)$$

Let's graphically represent the relationship between the height of the circular segment $h_{max}$, and the length of the chord, C, considering values of C ranging from 1 to 13. This range is chosen based on the following rationale: when the chord length, C, is less than 1, the height of the circle segment $h_{max}$, approaches 0. Additionally, given that the cutter diameter is 13 mm, the chord length, C, cannot exceed this value.

Dependencies $h_{\max} = f(C)$ are shown in Fig. 4.

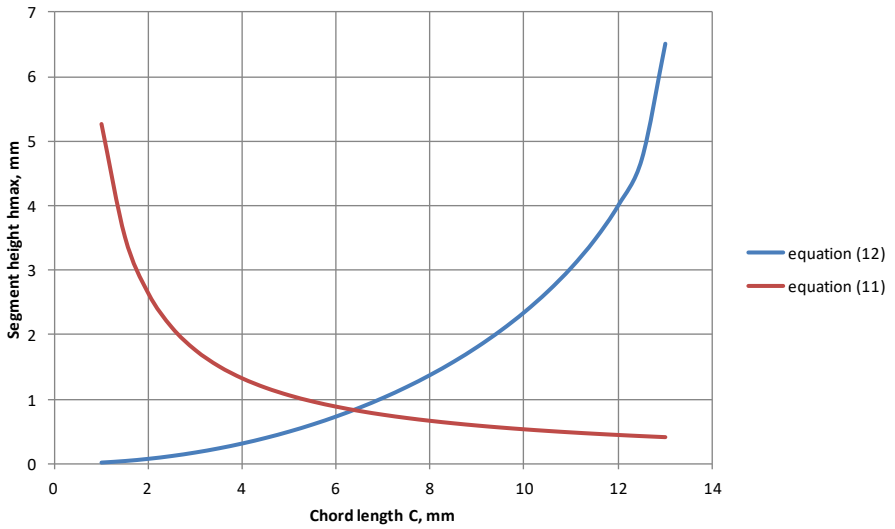


Fig. 4. Dependence of the height of the circle segment $h_{max}$ on the chord length C for formulas (11) and (12)

As can be seen from Fig. 4, the value of the chord length C, which is the solution to the system of equations (11), is C = 6.352 mm.

Then we find the value of the height of the circle segment $h_{max}$, which is the penetration depth of the PDC cutter per revolution

$$h_{\max} = \frac{k}{C} = \frac{5.263}{6.352} = 0.829 \text{ mm.}$$

Let us determine the ROP using formula (10)

$$ROP = h \cdot m \cdot n = 0.829 \cdot 4 \cdot 120 = 397.8 \, mm/min = 23.87 \, m/h.$$

The main difference from the traditional challenge of pressing a prismatic cutter with a pointed angle into the rock is that the mentioned cutter exerts force over an area shaped like a rectangle. In the current scenario, the PDC cutter influences the depressed rock across a region with a variable height, forming a segment of a circle.

As the PDC cutter descends deeper, the axial load $P_0$ increases, and the rock's resistance $H_r$, diminishes when pressed onto the cutter at a specific depth, $h_{max}$.

**Discussion**

The first issue addressed involved theoretical investigations into the factors contributing to the phenomenon of bit «hanging» during the drilling of intermittently hard rocks. A methodology for computing the distribution of forces

along the radius of the bit blades was formulated. Furthermore, two paddle-shaped tools were successfully patented. Additionally, a spud bit designed for drilling soft and medium-hard rocks underwent manufacturing and subsequent production tests, revealing a noteworthy 1.5-fold increase in tool life. Lastly, patented bladed PDC bits designed for drilling deep wells in rocks with intermittent hardness were developed.

The second issue addressed involved the patenting of a combined peak-shaped blade tool designed to navigate a technological well with a depth ranging from 750-800 m, cutting through soft rock layers and the underlying section of moderately hard, partly abrasive rocks. Detailed manufacturing blueprints for the tool were developed, accompanied by theoretical investigations determining the unit depth of penetration of the PDC cutter into the rock bottom per one revolution of the bit. A corresponding approximate formula was derived, accounting for factors such as the size (diameter) of the working layer of the cutter, its angle of inclination to the bottom, WOB, and rock hardness. Additionally, a methodology for utilizing the obtained formula was formulated. Subsequently, working drawings were prepared for the manufacturing and subsequent testing of a patented bit equipped with PDC cutters, specifically designed for drilling deep oil and gas wells.

Addressing the third issue involved collaboration between Satbayev University employees and the V. Bakul Institute for Superhard Materials of the National Academy of Sciences of Ukraine (ISM). The ISM took the lead in conducting the majority of experimental research, while the development work and production tests of the tools were carried out by the Satbayev University staff (Ratov, 2022).

The research aimed to develop an innovative composite diamond-containing material (DCM) with enhanced hardness and wear resistance. This material is intended for application in equipping rock-cutting tools, including drill bits and blade bits.

Experimental findings revealed that the structure of the diamond-matrix transition zone is notably influenced by the inclusion of $CrB_2$ powder in the initial charge composition, which contains 51% Fe – 32% Cu – 9% Ni – 8% Sn. The addition of 2% $CrB_2$ to this composite and the production of CAM samples through plasma-spark sintering resulted in a substantial increase in microhardness (from 3.86 GPa to 7.896 GPa). Simultaneously, there was a significant reduction in the wear rate, amounting to a 2-fold improvement.

Currently, only the first part of the problem has been partially addressed: a multilayer diamond core bit has been created and patented. In this design, impregnated layers featuring a «comb» profile are strategically placed within the matrix on a three-way helical surface. To produce a trial batch of these core bits, a manufacturing process was employed that involves adding 2% by weight of $CrB_2$ nanopowder to the diamond-containing charge, as recommended by the ISM (Mechnik, 2020: 13; Ratov, 2022).

Various manufacturers produced drill bits, and among them, the KSB-3M core bit, produced by SK Geoservice LLP, demonstrated the most favorable technical

and economic performance. During production testing at the geological site of Kazakhmys Barlau LLP, where rocks of VIII-IX and partially X categories were drilled, the KSB-3M core bit exhibited exceptional resilience, achieving a resource of 389 m with a 100% core yield. In comparison, the durability of Terekalmaz diamond core bits, employed for drilling at the same site, ranged between 200-250 m.

The most significant achievements were realized through research on geotechnological well drilling technology, involving a theoretical exploration of the bit «hanging» process and the development of specialized tools to eliminate this phenomenon. Challenges are anticipated in the precision manufacturing of patented blade tools designed for drilling deep oil and gas wells. In the imminent future, efforts will focus on producing and testing a combined tool equipped with both carbide and PDC components, designed for drilling geotechnological wells in a single operation. This combined tool is intended for cutting through sections of soft and medium-hard abrasive rocks, reaching depths of 700-800 m, with careful consideration of the economic efficiency associated with its usage.

The experimental validation of the derived formula for calculating a single recess of a PDC cutter per one revolution of the bit is scheduled for implementation in the future.

The most promising avenues for enhancing the efficiency of blade bits lie in the research and development of super-hard, wear-resistant materials. These materials are intended for use in equipping or enhancing the working elements of blade bits.

Following the outcomes of scientific investigations, a research and production laboratory dedicated to the manufacturing of diamond tools was established and fully equipped at Satbayev University in 2023. The primary objective of this facility, currently in its formative stage, is to create patented diamond tools in Kazakhstan. These tools will undergo laboratory and production testing at geological sites within the republic. If the results prove positive and considering economic factors, there are plans for their integration into industrial production.

**Conclusion**

1. Blade bits, incorporating PDC cutters, demonstrate a broad spectrum of applications in Kazakhstan, a trend that continues to expand over time. Drilling organizations actively contribute to this growth, with Satbayev University playing a significant role in advancing this process. Until recently, the university has primarily focused on theoretical studies, inventive activities, developmental work, and the methodical testing and statistical analysis of production results.

2. The establishment and operation of a research and production laboratory dedicated to the development of bladed rock-cutting elements will enable the validation of theoretical research outcomes through practical experiments. This initiative aims to swiftly design efficient tools made of metal, patented in Kazakhstan and internationally. The ultimate goal is to accelerate geological exploration and mining operations.

3. The correlation between the maximum penetration depth of an individual cutter in a PDC bit and its interaction parameters with the well bottom has been determined. In this analysis, the cutter was assumed to have a circular shape and a negative inclination angle to the well bottom. The penetration depth exhibits a direct proportionality to the WOB and an inverse proportionality to the hardness of the rocks. The relationship with the inclination angle of the cutter towards the bottom and the geometric parameters of the disintegrated rock layer is more intricate. Furthermore, the ROP is directly proportional to the maximum penetration depth of an individual cutter.

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