

REPUBLIC OF AZERBAIJAN

On the rights of the manuscript

ABSTRACT

of the dissertation for the degree of Doctor of Philosophy

**MODELING THE WELL DRILLING PROCESS IN
COMPLICATED CONDITIONS BASED ON THE
THEORY OF FUZZY SETS**

Specialty: 2523.01 - Well drilling technology

Field of science: Technical sciences

Applicant: **Igor Anatolyevich Piriverdiyev**

Baku - 2025

The dissertation work was performed at the Institute of Geology and Geophysics and Oil and Gas Institute of the Republic of Azerbaijan

Scientific consultant: Corresponding Member of ANAS, Doctor of Technical Sciences, Professor
Galib Mammad Efendiyev

Official opponents: Doctor of Technical Science, Professor
Yusif Murad Guliyev


PhD in technical sciences,
Associate Professor
Samad Ali Iskander Rza-zade

PhD in technical sciences
Namig Mammadgulu Aliyev

Dissertation Council ED 2.03 of Supreme Attestation Commission under the President of the Republic of Azerbaijan operating at the Azerbaijan State Oil and Industry University

Chairman of the Dissertation council: Doctor of technical sciences, Associate Professor

Arif Alekber Suleymanov

Scientific secretary of the Dissertation council: PhD in technical sciences, Associate Professor

Yelena Yevgenyevna Shmoncheva

Chairman of the scientific seminar: Doctor of Technical Sciences, Professor

Eldar Mammad Suleymanov

I confirm the signatures:

Scientific Secretary of ASOIU, PhD in technical sciences, Associate Professor


Narmina Tarlan Aliyeva



GENERAL CHARACTERISTICS OF THE STUDY

Relevance of the problem. The current level of development of technical means and technologies creates favorable conditions for obtaining more comprehensive information about the drilling process. This requires analysis of the acquired data, which in turn demands the application of methods enabling decision-making under uncertainty inherent in drilling operations. Such operational information is highly important and crucial, especially when drilling wells in areas with insufficient or absent prior information. The quality of this information largely determines the correctness of technological decisions in oil and gas well drilling, while low-quality data is one of the causes of erroneous decisions, ultimately leading to complications, accidents, and an overall decline in the technical and economic efficiency of drilling.

To date, a large body of research has been accumulated concerning the interaction between the drill bit and the rock. These studies propose methods and tools for determining the physical and mechanical properties and abrasiveness of rocks. They include experimental studies, investigations based on geological and geophysical data analysis, as well as classification methods. As a result, approaches have been developed to assess rock properties using core, cuttings, well logging data, and geological-technical information obtained during drilling. Overall, analysis of the completed works shows that today it is possible to improve the quality of decision-making through the integration of geological, geophysical, and technological data, which form the basis of technological solutions. This type of information may be obtained through various methods, but it contains uncertainties of different nature that affect its quality. Therefore, in acquiring and utilizing such information, it is necessary to employ modern methods of data processing and information analysis that account for these uncertainties. It is also critical to consider the conditions under which the drilling process occurs, namely: heterogeneity, fuzziness, and stochasticity of influencing factors. A reliable scientific basis for this can be provided by methods of control theory and decision-making under incomplete information,

which have recently gained wide development across various scientific and technical fields. It should be noted that, to date, these issues have not been sufficiently studied in drilling and require further attention.

Based on the above, the problem of modeling drilling processes and decision-making under uncertainty is highly relevant and represents both scientific and practical interest.

Objective of the study

Enhancement of the quality of information and the efficiency of decision-making in drilling operations through modeling based on fuzzy logic.

State of the art

The issues of decision-making in drilling, evaluation and prediction of rock drillability, as well as rock classification, have been addressed by numerous distinguished researchers who, over many years, conducted important theoretical and experimental investigations contributing to the development of the scientific foundations of drilling theory and practice. Their contributions cover a wide range, from experimental studies of rock properties to the optimization of drilling processes. Thanks to the efforts of researchers such as Alekseev L.A., Alekseev Yu.F., Artsimovich G.V., Baidyuk B.V., Bliznyukov V.Yu., Badalov R.A., Gelfgat Ya.A., Gulizade M.P., Eremin N.A., Litvinov M.A., Lukyanov E.E., Mirzajanzade A.Kh., Myslyuk M.A., Orlov A.V., Pogarsky R.M., Potapov Yu.F., Seid-Rza M.K., Fedorov V.S., Shreiner L.A., Eigeles R.M., Efendiyev G.M., Bingham M.G., Bourgoyne Jr. A.T. & Young F.S., Cuddy S.J., Cunningham R.A. & Eenink J.G., Eren T., Galle E.H. & Woods H.S., Garnier A.J. & van Lingen N.H., Graham J.W. & Muench N.L., Irawan S., and others, a considerable body of research has been accumulated, valuable both scientifically and practically.

Nevertheless, despite the substantial number of studies devoted to this subject, certain issues related to the methodology of drilling process modeling, selection of optimal drill bit types and operating parameters, as well as decision-making under complicated drilling conditions with uncertainties, have not yet been sufficiently explored and require deeper investigation.

Object of the research

The object of the present study is decision-making in the course of drilling operations under complicated geological and technical conditions.

Subject of the research

The subject of the study is the modeling of drilling processes and decision-making in situations characterized by uncertainty.

Research objectives

The research was aimed at addressing the following objectives:

- to review and analyze the current state of research concerning the problem under consideration;
- to examine problem situations arising during drilling within the framework of a general classification of uncertainties;
- to develop a methodology for modeling rock properties and classifying well sections into homogeneous intervals using statistical methods and fuzzy logic;
- to improve the methodology for real-time evaluation of complication-prone intervals on the basis of geophysical well logging and geological-technological investigations;
- to elaborate technological solutions aimed at enhancing the efficiency of drilling operations under complicated conditions.

Research methods

The stated objectives were accomplished using methods of mathematical statistics and fuzzy logic in data processing and information analysis. In classifying geological objects into homogeneous intervals in terms of drillability, a method and corresponding software were employed that combine geological section classification by a set of attributes with fuzzy cluster analysis. In decision-making concerning the selection of optimal drill bit types, operating parameters, and drilling fluid density, methods based on the principles of fuzzy set theory were applied.

Provisions submitted for defense:

- The methodology of a system for modeling drilling conditions and indicators, as well as for decision-making under uncertainty;

- Mathematical support for models and methods of decision-making in assessing geological section characteristics, based on probabilistic-statistical methods and fuzzy logic;

- Methodological approaches to decision-making in the selection of drilling technological parameters under uncertainty.

Scientific novelty:

1. An advanced classification scheme of uncertainties has been developed; the key factors giving rise to uncertainty in the course of drilling have been substantiated, and possible decision-making pathways in such situations have been identified;

2. A methodology has been proposed, based on geomechanical modeling, for assessing rock properties and subdividing well sections into homogeneous intervals with the use of statistical methods and fuzzy logic;

3. An improved computational scheme has been introduced, incorporating the prediction of loss-prone intervals by means of fuzzy cluster analysis and an evaluation of prediction reliability;

4. A scientifically substantiated computational framework has been proposed for determining the characteristics of the geological section, the boundaries of the “safe mud window,” and the required drilling fluid density, based on integrated geological, geophysical, and technological data and employing probabilistic-statistical methods together with fuzzy logic.

Practical significance

The analysis of drilling complications has resulted in the development of a fuzzy cluster analysis–based method enabling the early prediction of drilling fluid losses of varying severity. The solution was grounded in mathematical statistics and fuzzy set theory. Five distinct classes were identified, each characterizing a level of severity of drilling fluid loss, expressed in linguistic variables. On this basis, fuzzy models were constructed to capture the relationship between petrophysical properties and the volume of fluid loss. The obtained results facilitate timely decision-making to prevent losses and mitigate their consequences.

Furthermore, computations were carried out to subdivide the geological section into homogeneous intervals, to predict rock

lithology, and to compare the obtained results with design data. This was achieved by calculating weight functions for five key rock characteristics (porosity, permeability, lithology index, hardness, abrasiveness), followed by determination of harmonic mean values. These values were assigned to each rock type, and lithological prediction was carried out by selecting the type corresponding to the maximum harmonic mean among the weight functions. This approach enhances the reliability of lithological forecasts.

Reliability of the results

The reliability of the scientific statements and conclusions of the dissertation is ensured by the application of modern mathematical methods of data processing and information analysis, as well as by the consistency between theoretical research results and field observations, confirmed through appropriate evaluation criteria.

Approbation of the research results

The materials of the dissertation have been presented and discussed at the following scientific conferences:

- 12th International Conference on Application of Fuzzy Systems and Soft Computing, ICAFS 2016, 29-30 August 2016, Vienna, Austria;

- 19th International Conference "Rock Destruction and Metalworking Tools – Techniques, Technology of Their Manufacturing and Application", Truskavets, Ukraine, September 18–23, 2016;

- 9th International Conference on Theory and Application of Soft Computing, Computing with Words and Perception, ICSCCW 2017, 22-23 August 2017, Budapest, Hungary;

- 20th International Conference "Rock Destruction and Metalworking Tools – Techniques, Technology of Their Manufacturing and Application", Truskavets, Ukraine, September 17–22, 2017;

- 21st International Conference "Rock Destruction and Metalworking Tools – Techniques, Technology of Their Manufacturing and Application", Truskavets, Ukraine, September 16–21, 2018;

- 5th International Conference on Applied Linguistics Issues (ALI 2018), Turkey, Istanbul Ramada Encore, October 22-23, 2018;
- International School-Seminar of Young Scientists and Students. Oil & Geocology, 3-5 December 2018, Baku, Azerbaijan;
- International Scientific and Practical Conference “Current State and Prospects of Mature Fields Development”, Aktau, Kazakhstan, May 16–17, 2019;
- 22nd International Conference "Rock Destruction and Metalworking Tools – Techniques, Technology of Their Manufacturing and Application", Truskavets, Ukraine, September 15–20, 2019;
- 10th International Conference on Theory and Application of Soft Computing, Computing with Words and Perceptions – ICSCCW-2019. Czech Republic, Prague, 27-28 August, 2019;
- International Scientific and Practical Online Conference "Geological and Technological Aspects of the Development of Hard-to-Recover Hydrocarbon Fields", April 29, 2020, Aktau, Kazakhstan;
- XIXth International Conference "Geoinformatics: Theoretical and Applied Aspects", 11-14 May 2020, Kiev, Ukraine;
- 2020 International Symposium on Automation, Information and Computing (ISAIC 2020), December 2nd-4th, 2020, Online, Beijing, China;
- International Scientific and Practical Online Conference on “Modern Technologies in Science and Education”, Aktau, Kazakhstan, April 28, 2021;
- The International Scientific and Practical Conference "Heydar Aliyev and Azerbaijan oil strategy: Advances in oil and gas geology and geotechnologies", Baku, Azerbaijan, May 23-26, 2023;
- 16th International Conference on Applications of Fuzzy Systems, Soft Computing and Artificial Intelligence Tools – ICAFS-2023, 14-15 September 2023, Antalya, Turkey;
- 12th International Conference on Theory and Application of Soft Computing, Computing with Words and Perception and Artificial Intelligence – ICSCCW-2024, 26-27 August 2024, Budva, Montenegro.

Publications

Based on the materials of the dissertation, 24 publications have been issued, including 13 journal articles and 11 conference papers.

Institution where the dissertation was carried out

The dissertation was conducted at the Institutes of Geology and Geophysics, and Oil and Gas of the Ministry of Science and Education of the Republic of Azerbaijan.

Structure and volume of the dissertation

The dissertation comprises 162,765 characters and consists of an introduction, five chapters (the first chapter – 30 pages, the second – 19 pages, the third – 23 pages, the fourth – 16 pages, the fifth – 27 pages), conclusions, 22 figures, 8 tables, a list of references including 104 sources, and appendices.

MAIN CONTENT OF THE DISSERTATION

In the **Introduction**, the relevance of the problem addressed in the dissertation is substantiated, the objectives, research tasks, and methods for their solution are formulated, the main provisions submitted for defense are listed, and the scientific novelty and practical significance of the dissertation are demonstrated.

In **Chapter One**, a review is provided of studies devoted to the problems of modeling drilling processes and decision-making under uncertainty. These tasks are complicated by the uncertainty of the initial information and of the decision-making situations, expressed in multifactoriality, multicriteriality, inaccuracy, ambiguity, etc. To successfully solve these problems, taking into account the noted uncertainties, it is necessary to apply adequate methods that consider these circumstances, as well as to use the results of geological and technological investigations (GTI), which have become widespread in recent years. In general, the works carried out can be divided into four groups:

- studies devoted to the evaluation of rock properties and identification of intervals homogeneous in drillability;
- studies on the assessment of the compliance between bit design features and drilled formations, as well as the development of rate of penetration (ROP) models;

- studies focused on the assessment of complication intervals;
- decision-making studies.

In recent years, the theory of fuzzy sets has been applied to these problems. This approach makes it possible to make compromise decisions in conflict situations, to classify geological objects taking into account the fuzziness of boundaries, and to more accurately assess the risks of drilling emergencies. The works reviewed present the results of studies of the influence of various factors on bit performance indicators, on the nature of drilling complications, as well as the results of research into the conditions and causes of accidents. Attempts were made to analyze and evaluate the risks of accidents, complications, and incorrect decision-making, as well as to solve classification problems. Based on these results, several directions have been formed, along which the performed works can be grouped for a more convenient analysis. An overview is provided, analyzing the studies carried out in recent years by various domestic and foreign researchers.

The issues under consideration have been studied by such researchers as Alekseev L.A., Alekseev Yu.F., Artsimovich G.V., Baidyuk B.V., Bliznyukov V.Yu., Badalov R.A., Gelfgat Ya.A., Gulizade M.P., Eremin N.A., Litvinov M.A., Lukyanov E.E., Mirzajanzade A.Kh., Myslyuk M.A., Orlov A.V., Pogarsky R.M., Potapov Yu.F., Seid-Rza M.K., Fedorov V.S., Shreiner L.A., Eigeles R.M., Efendiyev G.M., Bingham M.G., Bourgoyne Jr. A.T. & Young F.S., Cuddy S.J., Cunningham R.A. & Eenink J.G., Eren T., Galle E.H. & Woods H.S., Garnier A.J. & van Lingen N.H., Graham J.W. & Muench N.L., Irawan S., and others. A comprehensive analysis of the literature on this issue made it possible to systematize the results of studies conducted in various organizations, to identify their general trends, and on this basis to define the objectives and tasks of the dissertation. In this chapter, methodological approaches are substantiated, and the principles underlying the research are formulated.

As a result of analyzing the current state of decision-making problems in drilling, it was established that insufficient attention has been paid to the development of a comprehensive classification system

for rocks, to modeling, and to decision-making regarding the choice of technological parameters. The main reason lies in the uncertainty of the studied conditions, objectives, and constraints. An improved structure of methodological principles for geomechanical studies of sections and decision-making under uncertainty during drilling is proposed.

In **Chapter Two**, an analysis is carried out of uncertainties present in the classification of geological objects and in making technological decisions in drilling.

Uncertainty is one of the causes of erroneous decisions in technological processes, particularly in drilling. Uncertainties arise in modeling, in the evaluation and analysis of rock properties, in assessing the influence of technological parameters on drilling indicators, and in decision-making. Uncertainty arises primarily because the data used to draw conclusions about the drilling process, and about the influence of various factors on drilling performance, are indirect in nature and applied in multi-stage schemes. Decision-making takes place under multifactorial and multicriterial conditions. The study of such complex systems, characterized by significant variability of parameters both with depth and spatially, is complicated by the presence of uncertainties in the results when solving classification, modeling, and drilling problems. This casts doubt on the validity of solutions obtained using traditional methods based on simplified models and approaches, which are “unable” to adequately account for the objectively existing uncertainty. It should be noted that the application of methods based on considering different types of uncertainty is not an alternative to traditional approaches to modeling complex systems and processes, but rather provides effective methods and tools for their study in different application areas.

The study of scientific terminological vocabulary in any field is one of the necessary and promising directions not only of modern linguistics but also of petroleum theory and practice. Like every other specialized area, the petroleum industry gradually develops its own linguistic and terminological framework serving the purposes of understanding and applying concepts [7].

During data collection and acquisition at a certain stage, it may turn out that: not all possible (incompleteness) or not all necessary (insufficiency) geological and technological information has been obtained under drilling conditions; for some elements, not exact descriptions but only sets to which they belong have been defined (underdefinition); some elements of the problem are described only by analogy with previously solved problems, providing only a “substitute” description, or a mismatch between the model and the real object occurs (inadequacy). The existence of these uncertainties (unreliabilities) is related either to temporary suspension of data collection, or to the lack of resources allocated for data collection and processing, or to insufficient measuring instruments.

In summary, uncertainty can be viewed both as a phenomenon and as a process. As a phenomenon, uncertainty manifests itself as insufficiency, incompleteness, and vagueness of information about the geological section. As a process, uncertainty is an event that occurs in making erroneous decisions due to imprecise formulations, reflected in the activities of the decision-maker. Both types of uncertainty constitute a single whole, mutually generating each other: the phenomenon is created by the process, and the process forms the phenomenon. Uncertainty manifests itself in the parameters of information at all stages of its processing. It is difficult to measure uncertainty; it is usually evaluated qualitatively (greater or lesser, higher or lower). Rarely is it assessed quantitatively, e.g., as a percentage.

Chapter Three of the dissertation is devoted to the improvement of data processing and information analysis methods for evaluating the characteristics of geological sections.

When preliminary information on the field section is available, the results of previously completed works serve as a basis for studying bit performance characteristics, which allow the construction of mathematical (deterministic, statistical) models of a similar type. These models later serve as basic ones and are refined by sequentially introducing various unaccounted factors. However, in each specific case, practical application of such models is complicated due to the heterogeneity of the geological section. Therefore, in subsequent

research, authors suggested dividing geological sections into units with homogeneous drillability, for which different classification methods were used depending on the case. Overall, analysis of the performed studies shows that improving the quality of decisions can currently be achieved through the use of integrated geological, geophysical, and technological information, which forms the basis of technological decision-making [6,12,17].

In recent years, geological and technological investigations (GTI) during drilling have been widely applied in global practice, making it possible to solve a number of problems in drilling when information about the section of the drilled well is absent or limited. The use of GTI results in combination with well logging (WL) allows a deeper study of the section, thereby improving the quality of decision-making.

In general, as analysis shows, solving the problems of modeling technological processes is significantly complicated by uncertainty, related to both random and fuzzy variables. Random variables express that the studied parameters may take on different values with certain probabilities. Fuzzy variables, on the other hand, convey the approximate nature in defining the values themselves. Moreover, fuzzy variables may be preferable in cases of insufficient statistical data and related information necessary for more reliable evaluations. Such assessments of the mechanical properties of rocks can be made using data on their physical properties obtained from well logging results, with the application of probabilistic-statistical methods and fuzzy set theory. The study of these dependencies made it possible to develop a substantiated calculation scheme for evaluating the characteristics of geological sections.

Optimal decision-making during drilling requires analysis of objectively existing qualitative and quantitative interrelations of various geological and technological factors identified in the course of drilling research. It also requires identifying correlations between geological, geophysical, mechanical, and technological characteristics of the section. The scheme presented below allows representation of the entire process from data collection to modeling, decision-making, and risk assessment. For clarity and to provide a more complete picture

of the sequence and content of the performed work, as well as the applied methods, the presented scheme of the “Berland triangle”¹ has been expanded according to our research. It also shows the initial information required for geomechanical studies, decision-making, and decision evaluation. The improved “Berland triangle” scheme is presented in Figure 1.

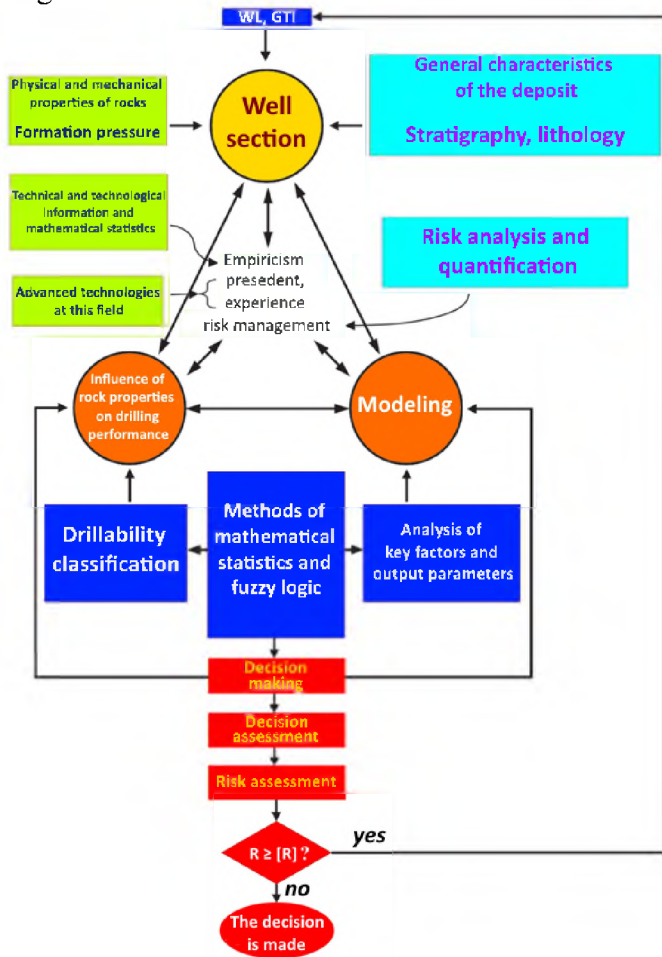


Fig. 1. Block diagram of geomechanical modeling and decision-making during drilling

¹ Burland J.B. The teaching of soil mechanics – a personal view. 1987, v. 3, pp. 1427–1447

The application of fuzzy logic, in combination with mathematical statistics, has made it possible to more accurately characterize geological sections, particularly to predict the lithology of drilled well sections based on a set of indicators (hardness, abrasiveness, lithology index, porosity, permeability) obtained from geological, geophysical, and technological investigations conducted during drilling. Analysis of the distribution of these parameters from well investigations has shown that, for each of the above indicators except permeability, the data follow a normal distribution law (permeability follows a lognormal distribution; therefore, its logarithmic values are used). If a rock is characterized by the distribution of hardness values (and/or abrasiveness, lithology index, porosity, permeability) with a mean value μ and standard deviation σ , then the fuzzy probability that the observed value of each parameter corresponding to this rock can be calculated using expression (1)²:

$$P(x) = \frac{e^{-(x-\mu)^2 / 2\sigma^2}}{\sigma\sqrt{2\pi}} \quad (1),$$

where $P(x)$ is the probability density that the observation x was measured within a dataset described by mean μ and standard deviation σ . In this case, the variables are hardness, abrasiveness, lithology index, porosity, and permeability, together with their corresponding mean values and standard deviations.

The mean and standard deviation are directly derived from datasets (from the results of GTI during drilling, core data, and well logging (WL)) for each lithotype.

Typically, a well section consists of several distinct lithological layers; in such cases, the observed value x of a parameter may belong to any of these lithotypes, with some being more probable than others. Each lithotype has its own mean value of hardness (and other rock

² Cuddy S.J. and Glover P.W.J. The Application of Fuzzy Logic and Genetic Algorithms to Reservoir Characterization and Modeling Soft Computing for Reservoir Characterization and Modeling, 2002, v. 1, pp. 219–241

characteristics) and its own standard deviation; thus, for each lithotype f , there exist parameter pairs μ_f and σ_f . Assuming that a measured characteristic belongs to lithotype f , the fuzzy probability that the observed value x was measured (obtained from experiments or WL) can be calculated using expression (1), substituting μ_f and σ_f . Similarly, fuzzy probabilities can be computed for all other lithotypes f and parameters. Such fuzzy probabilities are specific to one lithotype.

Of particular interest is the relationship between the fuzzy probability of each lithotype and the fuzzy probability of its mean (or most probable) value. This is achieved by normalizing equation (1). The relative fuzzy probability $R(x_f)$ that hardness x belongs to lithotype f , compared with the fuzzy probability of the mean value μ_f , can then be obtained. In this way, fuzzy probabilities can be compared across all lithotypes. To assess fuzzy probabilities for individual lithotypes, the relative frequency of occurrence of each lithotype within the well section must also be considered. This is achieved by multiplying the relative fuzzy probability by the square root of the expected frequency of lithotype f , which leads to the formula for fuzzy probability $F(x)$:

$$F(x_f) = \sqrt{n_f} e^{-(x-\mu_f)^2/2\sigma_f^2} \quad (2)$$

The fuzzy probability $F(x_f)$ is based exclusively on the measured hardness (from cores, GTI, or WL) x . The process is repeated for another parameter, e.g., porosity y . This step yields $F(y_f)$, the fuzzy probability that the measured porosity y belongs to lithotype f . The same procedure is repeated for other rock properties, resulting in fuzzy probabilities $F(z_f)$, etc. At this stage, five fuzzy probabilities ($F(x_f)$, $F(y_f)$, $F(z_f)$...) are available, each based on different lithological characteristics (x, y, z ...). These indicate the likelihood that lithotype f is the most probable. The fuzzy probabilities are then harmonically averaged to obtain the combined fuzzy probability:

$$C_f = \frac{5}{\frac{1}{F(k_{por})} + \frac{1}{F(k_{perm})} + \frac{1}{F(P_{Sh})} + \frac{1}{F(A)} + \frac{1}{F(\Delta\sigma)}} \quad (3)$$

This procedure is repeated for each lithotype f . The lithotype with the highest combined fuzzy probability is considered the most probable for the given set of parameters. The corresponding maximum fuzzy probability $C_j(max)$ enhances the reliability of lithological prediction. As an example, calculations were performed according to this scheme for one of the wells, and the results are presented in Fig.2.

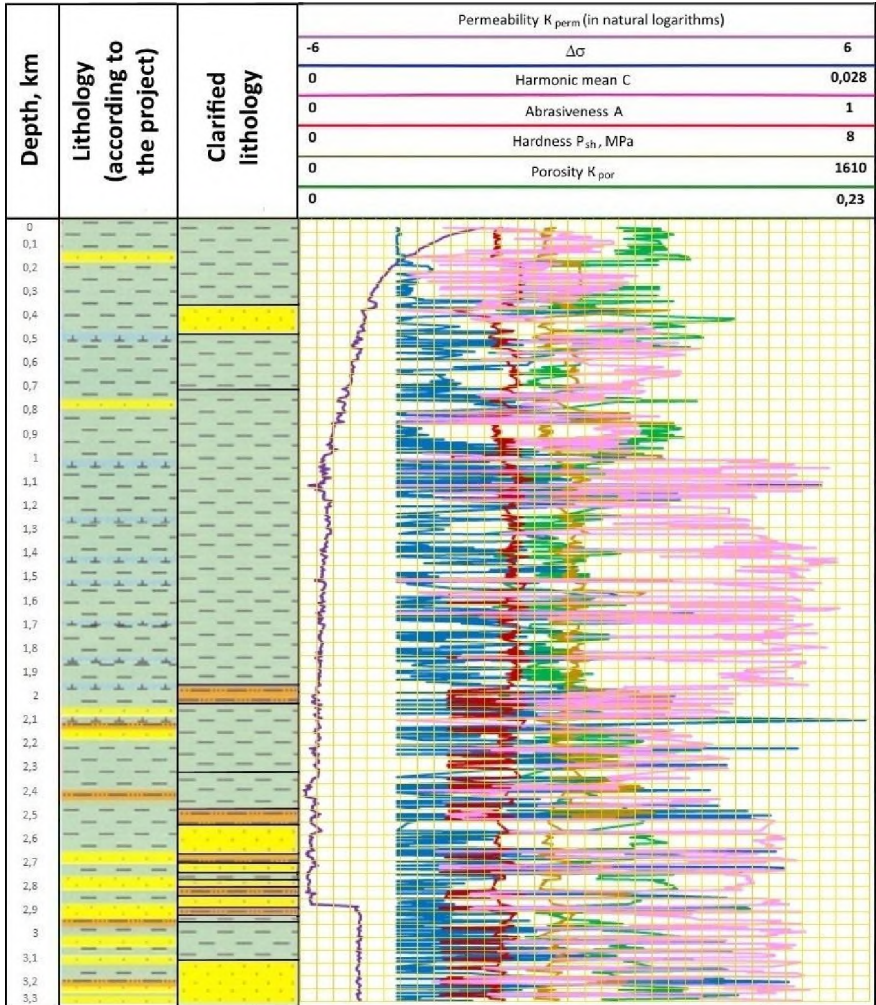


Fig. 2. Refined lithology assessment based on statistical analysis and fuzzy logic using the integrated data from WL and GTI

The figure illustrates two lithological columns: the one initially specified in the well project and the refined one obtained using the proposed calculation method [11,12,15]. A comparison is shown between the identified lithological types and their fuzzy probabilities. Lithological prediction using fuzzy logic is based on the assumption that a given lithology type can produce any response in the original data (e.g., well logs), although some responses are more probable than others. For example, it is most likely that clean sandstones will be highly porous, permeable, abrasive, and exhibit a high sigma-log parameter. Reliable lithological prediction requires comprehensive geological, geophysical, and technological data, which significantly increases the quality of predictive information.

Thus, the integration of geological and technological data enables more reliable predictions, thereby improving the efficiency of design decisions during drilling operations. This is particularly important for making correct operational choices. The accumulated body of research to date allows for real-time solutions to various tasks, including drill bit selection, adjustment of drilling parameters, and evaluation of complicated intervals.

The fourth chapter of the dissertation is devoted to the study of lost circulation patterns using the fuzzy clustering algorithm of geological objects based on petrophysical properties.

With the increasing volume of data processed, stored, and generated in industrial and scientific information systems, raw data processing has become increasingly challenging. Consequently, primary data processing is required for structuring, identifying features, summarizing, and sorting. For this purpose, classification and clustering processes are employed. Among the most widely used clustering methods are fuzzy clustering algorithms. The theory of fuzzy sets, first proposed by Zadeh in 1965³, introduced the concept of uncertainty in membership, which is described by a membership function. For each cluster, data points are assigned membership values, and fuzzy clustering algorithms allow clusters to grow into their natural shapes. In the Fuzzy C-Means (FCM) algorithm, each data point belongs to a cluster to a certain degree — this is called the

³ Zadeh L. Fuzzy Sets Information and Control, 1965, v. 8, pp. 338–353

degree of membership. This method, proposed by James Bezdek in 1981, is an improvement upon earlier approaches⁴. The principal advantage of this type of clustering is its flexibility: data points may belong to more than one cluster. It allows gradual membership of points in multiple clusters, with values ranging between 0 and 1.

Typically, works on determining the intensity of drilling fluid losses are conducted for each well individually. The intensity of losses is influenced by a number of factors, including lithological and petrophysical properties of the formations. Forecasting the expected values of loss intensity at the well design stage, based on the analysis of previously drilled wells, provides a significant reserve for reducing drilling costs in intervals characterized by formations prone to losses. The severity of losses may vary and can be assessed using cluster analysis. Accordingly, our objective was to apply fuzzy cluster analysis to evaluate the frequency of such drilling complications as drilling fluid losses. Drilling data were collected, including measurements that enabled the determination of loss intensity. Depending on the nature of the input information, two approaches were proposed: a statistical one and a fuzzy cluster analysis approach. The data were subjected to statistical and fuzzy clustering using the c-means algorithm and the corresponding software. As a result, five clusters were identified, each characterized by a relative level of loss, lithological features of the formations, and intensity of drilling fluid lost circulation.

As studies have shown, the severity of fluid losses is significantly influenced by the filtration-capacity properties of the formation. Attempts to evaluate their effect on fluid losses are complicated by various uncertainties. To assess the impact of geological formation properties on the occurrence and severity of fluid losses under conditions of limited or incomplete information, a relationship between petrophysical properties of the rocks and the severity of losses was established using fuzzy cluster analysis. This approach is particularly valuable for early diagnostics and risk assessment of fluid losses [1,5].

⁴ Bezdek J.C. Pattern Recognition with Fuzzy Objective Function Algorithms. Plenum Press, New York, 1981, 256 p.

As a result of the conducted research, a so-called "hybrid" clustering procedure was proposed, which combines fuzzy cluster analysis with a statistical method of information processing that includes entropy calculation. Refinement of the results obtained through this method is achieved by applying clustering procedures based on fuzzy logic along with probabilistic-statistical evaluations. Implementation of the FCM (Fuzzy C-Means) algorithm yielded membership functions, cluster allocation, severity levels of fluid losses, entropy values, and indicators for evaluating clustering quality. The calculated entropy values confirm a relatively high level of clustering performance, since the resulting clusters are internally compact and externally heterogeneous.

Chapter Five of the dissertation addresses the problem of decision-making in drilling under complicated conditions.

The problem of optimal drilling process control has become one of the most important in recent years. The complexity of this task arises from the heterogeneity of the drilled formations and the limited availability of information regarding both their properties and their effect on drilling performance. Effective drilling management requires in-depth analysis of multiple factors, justification of criteria, model design methodologies, optimal decision-making strategies, and risk evaluation for erroneous decisions. The uncertainty of many geological-technological parameters, along with ambiguities in defining objectives and constraints, further complicates optimal decision-making. The development of drilling management systems inevitably requires new models that are capable of adapting to uncertain conditions as more data are accumulated. Such models can be effectively implemented using various mathematical tools, including fuzzy set theory. When drilling under conditions of abnormally high formation pressures, particular attention must be paid to drilling fluid parameters and well design, where accurate assessment of geological conditions plays a decisive role. Uncertainties in pore pressure values frequently lead to complications such as kicks and blowouts, which may ultimately result in well loss and severe financial damage. Therefore, timely assessment of pore pressure is essential for selecting the appropriate drilling fluid density.

The development of modern information-retrieval and monitoring systems allows for optimal control of drilling parameters at a more advanced level. Fig. 3 presents a decision-making scheme depending on the type of available input information.

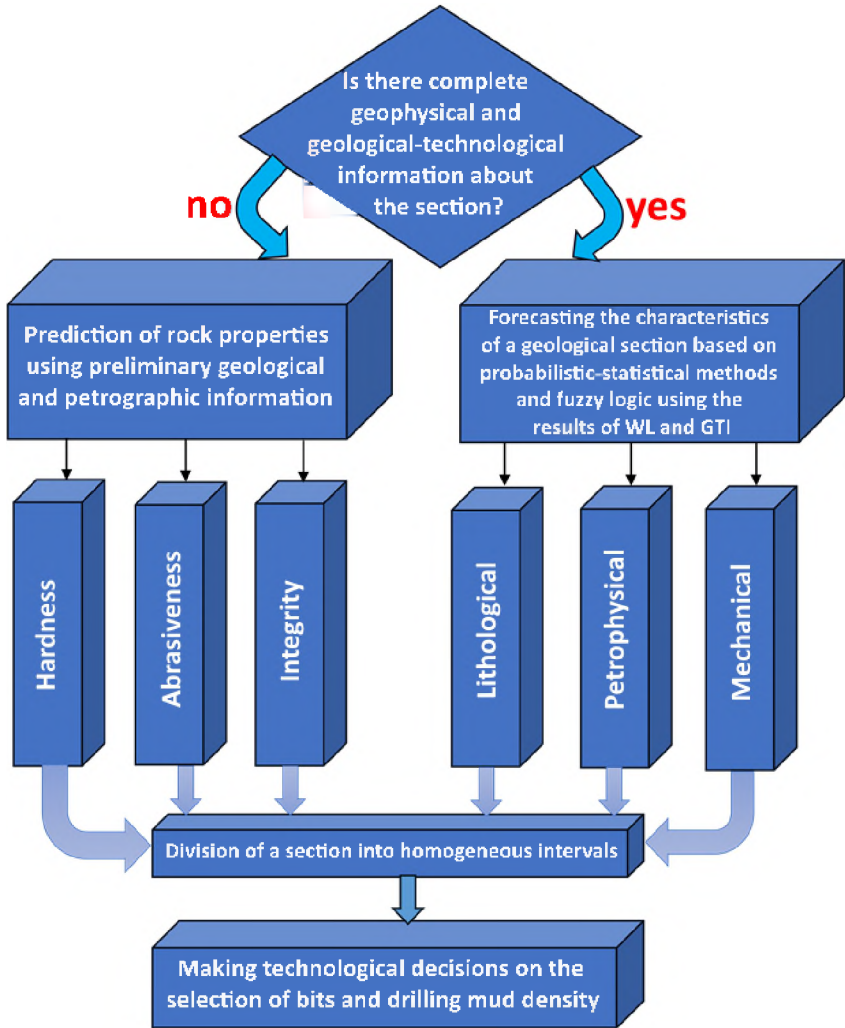


Fig. 3. Decision-making scheme depending on the type of input information

To date, a large body of research has accumulated on bit–rock interaction, with proposed methods for evaluating physical–mechanical properties of rocks, mechanisms of rock destruction, and factors influencing drilling efficiency. Existing methods of optimizing drilling parameters can be grouped into three categories: expert methods based on physical modeling, analytical methods, and field-based methods. In practice, it is usually sufficient to analyze prior drilling experience in the target area (or analogous fields with comparable geological conditions), or to conduct experimental drilling tests with new bits and technologies. The first group of methods requires a vast amount of data. The second group is based on modeling the impact of a single cutting element of the bit on the rock, which requires large volumes of core material that are practically impossible to obtain. The third group involves costly and time-consuming field experiments. According to both natural experiments and accumulated research, no universal laws describing the drilling process exist. Modern drill bits are often capable of drilling through several heterogeneous formations in one run, which further limits the applicability of these methods.

For effective use, a proper model based on real-time drilling monitoring is required. In recent years, a new direction has emerged and evolved — geological-technological investigations during drilling. A well-grounded evaluation of bit type compatibility with rock properties and drilling parameters, directly in the course of drilling, has allowed for maximum utilization of bit performance potential.

Based on the analysis of integrated geophysical (WL) and geological-technological (GTI) data, a method for calculating the limits of the "safety mud window" was developed, relying on fuzzy logic. This method provides a scientifically justified selection of drilling fluid density for safe drilling operations (Fig. 4). Within the framework of fuzzy set theory, the objective is to ensure high rates of penetration, while the constraint is to maintain mud density between the pore pressure gradient and the fracture pressure gradient. Both the objective and constraint are inherently uncertain in their formulations, making fuzzy logic an appropriate tool [20,21].

To establish the safety window, the following parameters must be determined: pore pressure, fracture pressure, minimum horizontal stress, maximum horizontal stress, vertical stress, and shear failure gradient. Based on the determined safety mud window, actual mud density values are assigned and applied in drilling practice.

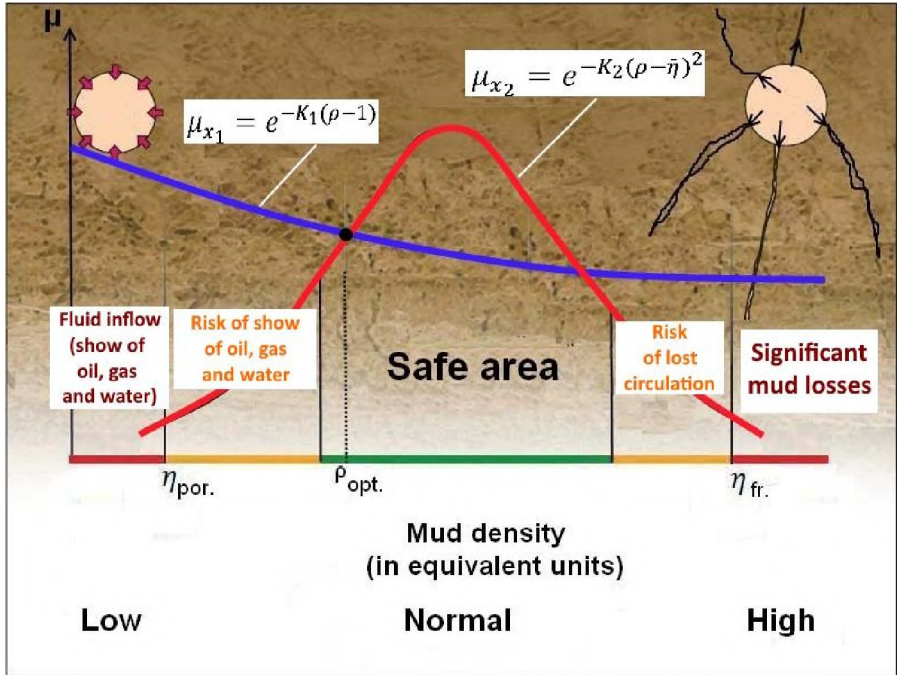


Fig. 4. Membership functions of goals and constraints

MAIN CONCLUSIONS AND RECOMMENDATIONS

1. Analysis of the current state of decision-making in drilling operations has demonstrated insufficient development of a unified system for rock classification, process modeling, and parameter optimization, primarily due to uncertainties in conditions, objectives, and constraints.

2. An improved methodological framework has been proposed for geomechanical studies of formations and for decision-making during drilling under conditions of uncertainty.

3. An enhanced classification scheme of uncertainties applicable to drilling processes has been developed, which enables the justification of modeling methods and decision-making strategies through proper identification of uncertainties.

4. An algorithm has been developed for evaluating lithological, reservoir, and strength properties of formations and their drillability, based on mathematical statistics and fuzzy logic. The implementation of this algorithm improved the quality of information and predictive assessments.

5. A “hybrid” clustering procedure has been proposed, combining fuzzy cluster analysis with statistical information processing, including entropy calculations. Refinement of clustering results was achieved through fuzzy logic and probabilistic-statistical methods.

6. Application of the FCM algorithm enabled the calculation of membership functions, identification of clusters, determination of fluid loss severity levels, entropy calculation, and evaluation of clustering quality. The entropy values confirmed that the resulting clusters are internally compact and externally heterogeneous.

7. Based on integrated WL and GTI data, a method was proposed for evaluating the limits of the “safety window” using fuzzy logic, which provides a scientific justification for selecting drilling fluid density for safe drilling operations.

8. A predictive scheme has been developed for drilling performance indicators and decision-making regarding bit selection and drilling fluid density, taking into account rock properties and the nature of available information.

9. Practical recommendations have been developed and proposed for implementation, focusing on selecting technological solutions under uncertainty. The resulting economic benefits are associated with higher drilling rates and reduced drilling fluid density. These results are documented in an official report issued by the drilling company «Gulf Drilling».

The main content and results of the dissertation have been published in the following works:

1. Efendiyev, G.M., Mammadov, P.Z., Piriverdiyev, I.A., Mammadov, V.N. Clustering of geological objects using FCM-algorithm and evaluation of the rate of lost circulation // 12th International Conference on Application of Fuzzy Systems and Soft Computing, ICAFS 2016 / 29-30 August 2016, Vienna, Austria / Procedia Computer Science (ELSEVIER), Volume 102, 2016, pp. 159-162

2. Эфендиев, Г.М., Джанзаков, И.И., Кирисенко, О.Г., Пиривердиев, И.А., Сарбопеева, М.Д., Буктыбаева С.К. Исследование влияния различных факторов на результаты взаимодействия породоразрушающего инструмента с породой и принятие решений // XIX Международная конференция «Породоразрушающий и металлообрабатывающий инструмент – техника, технология его изготовления и применения» / г. Трускавец, Украина. 18-23 сентября 2016 г., с. 124-132

3. Efendiyev, G.M., Mammadov, P.Z., Piriverdiyev, I.A., Sarbopeyeva, M.D. Selection of the best combination of bit types and technological parameters during drilling, taking into account uncertainty // 9th International Conference on Theory and Application of Soft Computing, Computing Perception, ICSCCW 2017 / 22-23 August 2017, Budapest, Hungary / Procedia Computer Science (ELSEVIER), Volume 120, 2017, pp. 67-74

4. Эфендиев, Г.М., Джанзаков, И.И., Кирисенко, О.Г., Пиривердиев, И.А., Гурбанов, В.Ш., Буктыбаева, С.К. Анализ и оценка эффективности принимаемых решений при бурении скважин // XX Международная конференция «Породоразрушающий и металлообрабатывающий инструмент – техника, технология его изготовления и применения» / г. Трускавец, Украина, 17-22 сентября 2017 г., с. 153-160

5. Efendiyev, G.M., Mammadov, P.Z., Piriverdiyev, I.A., Mammadov, V.N. Estimation of the lost circulation rate using fuzzy clustering of geological objects by petrophysical properties // Visnyk Taras Shevchenko National University of Kyiv, Geology, – 2018. – Vol. 2(81). – pp. 28-33

6. Эфендиев, Г.М., Кулиев, Г.Г., Джанзаков, И.И., Пиривердиев, И.А. Принятие решений при бурении скважин в осложнённых условиях с учётом неопределённости // Породоразрушающий и металлообрабатывающий инструмент – техника и технология его изготовления и применения: Сборник научных трудов. – Вып. 21. – Киев: ИСМ им. В. Н. Бакуля НАН Украины, 2018, с. 11-17

7. Efendiyev, G.M., Piriverdiyev, I.A. Terminological uncertainties in oilfield theory, practice and decision-making // Selected Papers E-book of the 5th International Conference on Applied Linguistics Issues (ALI 2018) / Turkey, Istanbul Ramada Encore, October 22-23, 2018, pp. 79-83

8. Piriverdiyev, I.A. Decision-making during drilling, taking into account uncertainty // International School-Seminar of Young Scientists and Students. Oil & Geocology / 3-5 December 2018, Baku, Azerbaijan

9. Пиривердиев, И.А., Сарбопеева, М.Д., Асадова, Г.Ш. Анализ процессов моделирования и принятия решений при бурении скважин с учетом неопределенности // Серия геологии и технических наук. Известия Национальной Академии Наук Республики Казахстан, – 2019. – №1 (433). – с. 23-31

10. Пиривердиев, И.А. Оценка влияния геологических условий на характер осложнений и принятие решений при бурении скважин // Материалы международной научно-практической конференции «Состояние и перспективы эксплуатации зрелых месторождений» / Актау, Казахстан, 16-17 мая 2019, том 2, с. 180-186

11. Efendiyev, G.M., Mammadov, P.Z., Piriverdiyev, I.A. Modeling and Evaluation of Rock Properties Based on Integrated Logging While Drilling with the Use of Statistical Methods and Fuzzy Logic // 10th International Conference on Theory and Application of Soft Computing, Computing with Words and Perceptions, ICSCCW-2019 / 27-28 August 2019, Prague, Czech Republic / Advances in Intelligent Systems and Computing book series (Springer), 2020, Volume 1095, pp. 503-511

12. Эфендиев, Г.М., Кулиев, Г.Г., Пиривердиев, И.А., Джанзаков, И.И., Буктыбаева, С.К. Методы и средства повышения качества информации при принятии решений в управлении процессом бурения скважин // Породоразрушающий и металлообрабатывающий инструмент – техника и технология его изготовления и применения: Сборник научных трудов. – Вып. 22. – Киев: ИСМ им. В.Н. Бакуля НАН Украины, 2019, с. 52-62

13. Piriverdiyev, I.A. The use of integrated geological, geophysical and technological information to divide a section into homogeneous intervals and make decisions // XIXth International Conference "Geoinformatics: Theoretical and Applied Aspects" / 11-14 May 2020, Kiev, Ukraine, pp. 1-5

14. Piriverdiyev, I.A. Division of the geological section into homogeneous drillability intervals based on the results of modeling the properties of rocks in the drilling process // ANAS Transactions, Earth Sciences, – 2020. – Vol. 2. – pp. 33-39

15. Efendiyev, G.M., Isayev, R.A., Piriverdiyev, I.A. Decision-Making while Drilling Wells based on the Results of Modeling the Characteristics of Rocks using Probabilistic-Statistical Methods and Fuzzy Logic // International Symposium on Automation, Information and Computing (ISAIC 2020) / 2-4 December 2020, Beijing, China / Journal of Physics: Conference Series, – 2021. – Volume 1828. – pp. 1-7

16. Isayev, R.A., Piriverdiyev, I.A. Study of geological cross-sections for making design and engineering decisions while drilling under uncertainty // ANAS Transactions, Earth Sciences, – 2021. – Vol. 2. – pp. 69-74

17. Эфендиев, Г.М., Исаев, Р.А., Пиривердиев, И.А., Джанзаков, И.И., Буктыбаева, С.К. // Информационное обеспечение процесса бурения скважин на основе применения современных методов, технических средств и технологий / Инструментальное материаловедение, Том 24, № 1, Киев, 2021, с. 19-26

18. Efendiyev, G.M., Piriverdiyev, I.A., Guluzade, K.P., Kasanova, A.G. Analysis of the main factors influencing the efficiency of the drilling process based on complex information about

the section using the methods of mathematical statistics and fuzzy logic // The International Scientific and Practical Conference "Heydar Aliyev and Azerbaijan oil strategy: Advances in oil and gas geology and geotechnologies" / Baku, Azerbaijan, May 23-26, 2023, pp. 691-695

19. Karazhanova, M.K., Moghanloo, R.G., Piriverdiyev, I.A. Оценка характеристик надежности нефтепромыслового оборудования и принятие решений в условиях неопределенности (Assessment of oilfield equipment reliability characteristics and decision-making under uncertainty) // Yessenov Science Journal, – 2023. – № 2 (45). – с. 165-170

20. Piriverdiyev, I.A., Efendiyev, G.M., Karazhanova, M.K., Kasanova, A.G. Choosing Mud Density Based on Geomechanical Modeling and Fuzzy Logic // 16th International Conference on Applications of Fuzzy Systems, Soft Computing and Artificial Intelligence Tools – ICAFS-2023 / 14-15 September 2023, Antalya, Turkey / Lecture Notes in Networks and Systems (Springer), Volume 1142, pp. 103-108

21. Efendiyev, G.M., Piriverdiyev, I.A., Karazhanova, M.K., Asgarov, M.B. Принятие решений по выбору оптимальной плотности бурового раствора на основе геомеханического моделирования и нечеткой логики (Decision making on the selection of optimum mud density based on geomechanical modeling and fuzzy logic) // Yessenov Science Journal, – 2024. – № 3 (48). – с. 133-140

22. Efendiyev, G.M., Karazhanova, M.K., Piriverdiyev, I.A., Kasanova, A.G., Asgarov, M.B. Assessment of the characteristics of the geological section of wells based on probabilistic-fuzzy analysis of complex geophysical and geological-technological information // SOCAR Proceedings, – 2024. – No.3. – pp. 3-8

23. Efendiyev, G.M., Karazhanova, M.K., Piriverdiyev, I.A., Kasanova, A.G., Asgarov, M.B. Study of Drilling Mud Losses Based on Fuzzy-Probabilistic Analysis of Information // 12th International Conference on Theory and Application of Soft Computing, Computing with Words and Perception and Artificial Intelligence – ICSCCW-2024 / Budva, Montenegro, August 26–27, 2024

24. Kassanova, A.G., Efendiyev, G.M., Piriverdiyev, I.A., Karazhanova, M.K., Akhmetov, N.M. Assessment of the characteristics of the geological section of wells based on complex geophysical and technological information // News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences, – 2025. – Volume 4 (472). – pp. 184-198

Personal contribution of the applicant

Papers [8,10,13,14] were carried out independently.

In papers [1,3,5,6,9,11,12,15,16,20,21,22,23,24], the applicant participated in the problem formulation, conducting research, and summarizing the results.

In papers [2,4,7,17,18,19], the applicant contributed to the problem formulation and the generalization of the results.



The defense of the dissertation will take place on September 23, 2025, at 11:00, at the meeting of the Dissertation Council ED 2.03, operating on the basis of the Azerbaijan State Oil and Industry University.

Address: AZ1010, Baku, 227 D. Aliyeva Street

The dissertation is available at the library of the Azerbaijan State Oil and Industry University.

The electronic version of the dissertation and the abstract is posted on the official website of the Azerbaijan State Oil and Industry University.

The abstract was distributed to the relevant addresses on 20 August 2025

Signed for print: 01.07.2025
Paper format: A5
Volume: 34958
Number of hard copies: 20