APPLICATION OF GEOPHYSICAL WELL LOGGING DATA TO ASSESS THE PHYSICAL-MECHANICAL PROPERTIES OF ROCKS

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Abstract

This article discusses geophysical methods, as a geological tool, to determine the physical and mechanical properties of carbon-bearing rocks of the Karaganda coal basin. The mine fields of the Karaganda basin are distinguished by the complexity of the geological conditions, the variability of the technological characteristics of the coal, and the physical and mechanical properties of the coal-bearing rocks, both in the area of the basin and with the depth of the coal seams. In connection with this, the requirements for studying the composition and physical and mechanical properties of carbon-bearing rocks are increasing. From the above, the problem of developing the scientific foundations of creating methods for predicting the structure, composition, and physical and mechanical properties of an array of rocks with the use of a system-factor analysis of the formation and transformation of coal formations becomes topical. This will allow raising to a qualitatively new level the assessment of the physical and mechanical properties and the prediction of the stability of the rocks roof in the mine workings. To achieve the goal, we used such geophysical parameters, as $\rho_{к}$ – electrical resistance of rocks, d – borehole diameter reflecting the physical state of the rock mass to characterize the physical and mechanical properties and the stability of the roofs of the coal seams. As a result, multidimensional mathematical equations for typical rocks of the basin – argillites, aleurolites, and sandstones – are derived, showing the relationships between their physical and mechanical properties and geophysical parameters.

Introduction

Mining production in Kazakhstan in connection with the introduction of mechanization and automation of technological processes of mining in mines and the transition to deep horizons, poses a number of complex problems for science. One of the main geological problems is to predict the coal seams rocks roof stability of the Karaganda basin. In order to solve it, such methods and research methods are needed, which allow to determine the physical and mechanical properties of rocks under the conditions of the developed mine massif in the pre-design stage. The solution of this task will give the opportunity to study the conditions of stability of the roof rocks with different nature of their structure, to establish the parameters of rational and safe cleaning works with the choice and types of mechanized support in the conditions of automated mining enterprises (DAVID, 2010; McCANN, 1992; McNALLY, 1987; PENG SUPING, 2007).

The study of the physico-mechanical properties of roof rocks of coal beds are the basis for the design, construction and operation of mining enterprises, correct selection of the optimal parameters of mining engineering processes, laying new horizons, rationing of mining operations, for calculating mining pressure, predicting the stability of mine workings and the method of controlling the roof of coal seams prepared for mining, as they reflect the quantitative characteristics of the rocks state. Tasks related to the determination of the physical and mechanical properties and the stability of the roof can be solved using geophysical methods such as the seismic method [6], electrometry and caliper logs to study the complete section of rocks. Geological and geophysical models of physical and mechanical properties and prediction of the stability of roof rocks of coal seams can be created using seismic (LI, 2018; ZHANG, 2007), geophysical methods (WILSON, 2014; HAN, 2018), drilling and laboratory studies (HAO, 2016) to study the full characteristics of the geological section (REN, 2018; HAO, 2016; JUAN, 2015).

Karaganda coal basin is located in Central Kazakhstan. In terms of coal reserves and quality, it occupies a leading position among the largest coal-bearing basins in the world. In the basin extended in the latitudinal direction for 120 km with an average width of 60 km, four coal-bearing areas are distinguished: Tentek, Sherubaynura, Karagandy and Verhnesokur (Figure 1).

Carboniferous coal-bearing deposits with a total thickness of about 4,000 m are divided into seven suites according to coal saturation, lithological composition, fauna, flora and other characters: akkuduk, ashylyayryk, karagandy, nadkaragandinskaya, dolinskaya, tentek, shahan.

In the Carboniferous, deposits of the karagandy, dolinskaya and partly ashylyayryk and tentek suites are productive. In this stratum, there are more than 80 layers and seams of coal with a total capacity of up to 110 m. The thickness of coal seams increases in the basin from west to east, and within each region from north to south (ATLAS, 2004).

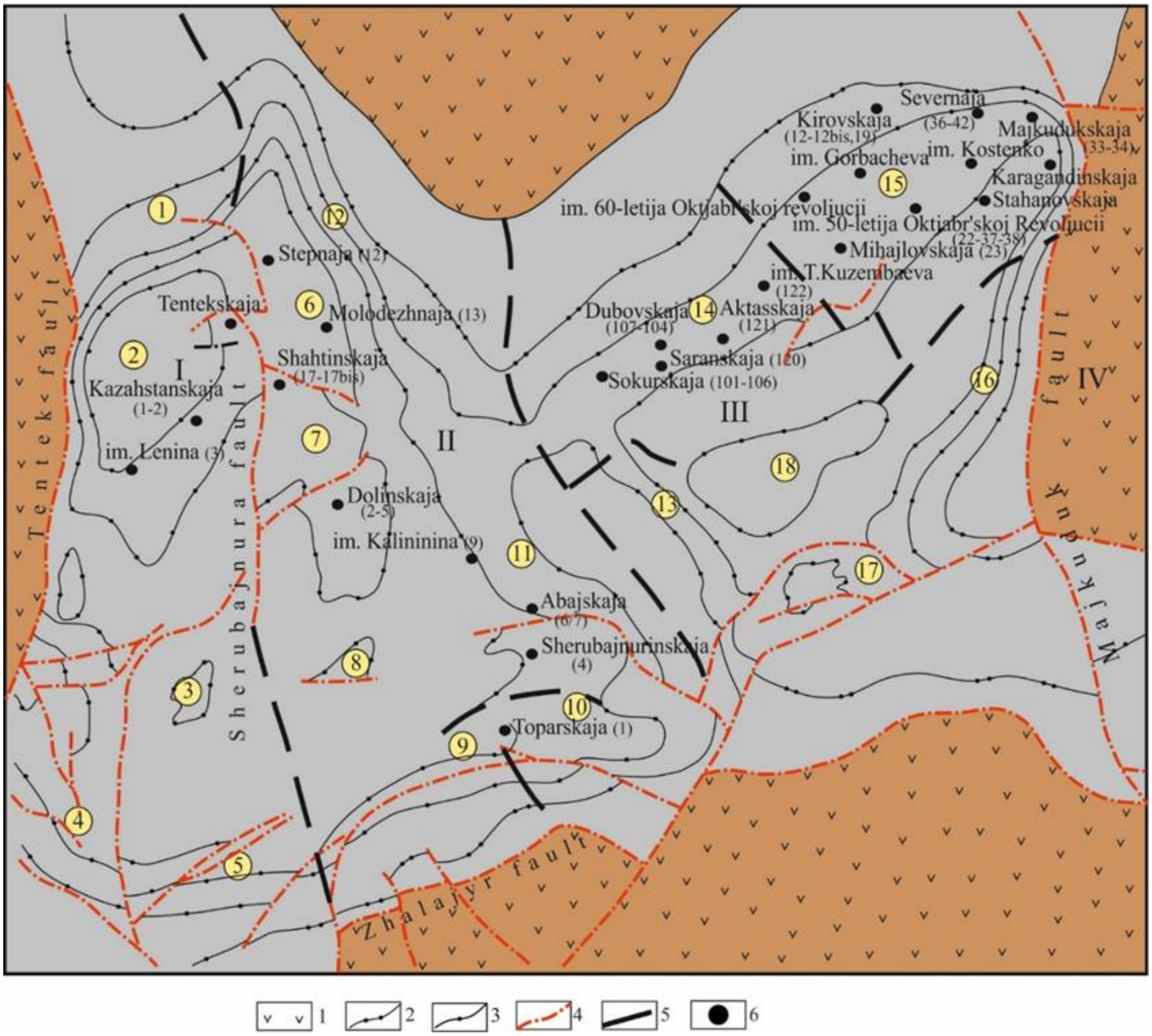

__Figure 1__ – Schematic geological map of the Karagandy basin: 1 – pre-Carboniferous deposits; 2 – lower border of the ashhylyairyk suite; 3 – boundaries of the karagandy suite; 4 – faults; 5 – borders of coal-bearing areas and sites; 6 – operating mines, in numbers – old name. Coal-bearing areas: I – Tentek; II – Sherubainura; III – Karagandy, IV – Verkhnesokur. Basin areas (numbers in circles): 1 – Manzhin; 2 – Tentek; 3 – Karagok; 4 – Sasykkol; 5 – Taskamys; 6 – Karazhar-Shahan; 7 – Dolinka; 8 – Kalpak; 9 – Kishkenekol; 10 – Southern; 11 – Central; 11 – Northern; 13 – Alabas; 14 – Saran; 15 – Promyshlennyi; 16 – Maikudyk; 17 – Taldykudyk; 18 – Dubovka.

Method

The proposed method for predicting the physical and mechanical properties and stability of rocks in the mine workings according to a complex of geophysical methods is based on the data of field observations in the clearing and preparatory workings of the mines of the Karaganda basin. This method of interpreting geophysical data allows the determination of the physical and mechanical properties of rocks continuously throughout the well section in their natural occurrence.

To determine the physicomechanical properties of rocks from geophysical parameters, we used the data of the AR (apparent electrical resistance of the rocks) and caliper data (McNALLY, 1987: ZHANG, 2007: GRECHUHIN, 1980).

Specific electrical resistance of rocks ($\rho_п$) determined by AR diagrams - by the method of lateral logging sensing (LLS). When comparing values ρ_{rock} and ρ_r (determined graphically from the charts of the AR) it was established the existence of a natural connection between them. Analytical dependency between $\rho_п$ and $\rho_к$ for the rocks of the coal suites of the basin obeys a linear law:

$$P_{rock} = a\,\rho_r + b \qquad (1)$$

The values of the empirical coefficients of equation (1) for the calculation of $\rho_п$ are given in table 1 (MILLER, 1965).

Table 1 – The values of the empirical coefficients of the equation (DAVID, 2010).

Rock	Gradient probe	Coefficient values		Correlation coefficient *r*	Mean standard deviation σ, %
		a	***b***		
Argillite	Standart	0,79	1,0	0,90	10,1
	Small	1,02	1,6	0,80	21,4
	Small	1,10	-	0,80	21,4
Aleurolite	Standart	0,59	7,7	0,83	11,5
	Small	1,00	2,6	0,46	26,2
	Small	1,10	-	0,46	26,2
Sandstone	Standart	0,56	10,7	0,84	14,1
	Small	0,90	8,6	0,60	28,7
	Small	1,13	-	0,60	28,7

A closer connection was obtained when correlating $\rho_п$ with $\rho_К$, obtained by a standard gradient probe A1,2M0,1N. The use of $\rho_К$, values for these purposes, determined with the help of a small gradient probe A0,3M0,03N, gives a large scatter and a small closeness of connection. This is apparently due to the significant effect of well conditions on the recording results due to the small size of the probe and the small depth of the study. The process of determining $\rho_п$ is rather laborious, and in the absence of data from resistivity and caliper even impossible, therefore, the use of the dependencies obtained (Table 1) greatly simplifies the task of determining $\rho_п$. Moreover, a comparability condition (obeys a linear law) with a high value of the correlation coefficient is found between the $\rho_п$ and $\rho_К$ values and to evaluate the physical and mechanical properties of rocks you can use with their apparent resistivity, determined from the AR diagrams of a standard gradient probeA1,2M0,1N.

To study the section of exploratory wells in combination with other geophysical methods is widely used and the method of caliper measurement or measurement of the diameter of the wells (DW). However, the practical use of its results is still very limited. The method is based on the study of the well section by the nature of changes in the diameter of the well during drilling. The diameter of the well is measured by a caliper КМ-1 and the data is recorded on the tape in the form of a continuous diagram - cavernograms.

The increase in the actual diameter of the well in the process of drilling against the nominal occurs over the entire depth of the well, especially in rocks less durable and less water resistant (Figure 2). Argillites have the greatest cavernosity, sandstones have the lowest, and siltstones occupy an intermediate position. Coal seams exhibit a very diverse cavernosity: from high cavernosity, equal to that in argillites, to insignificant, as in sandstones. Sometimes in coal seams and layers, wells are drilled and glands are formed. Often, even within a single thick layer (for example, layer $д_6$) there is also high cavernosity and formation of «glands» in boreholes. This phenomenon is apparently due to a change in the viscosity of the drilling fluid, different ash content and mechanical strength of individual packs of a complex formation and, as a result, the selective manifestation of the adsorption capacity of individual packs or seams of coal.

Comparison of cavernograms shows that with an increase in the standing time of the walls of the well, an increase in its diameter and cavernosity occurs. The initially formed insignificant cavernosity continues to develop over time within the same intervals where they originated. A significant increase in cavernosity over time is observed in argillites. In the intervals of occurrence of aleurolite and sandstone, both at the beginning and subsequently, no local cavities are formed, but a general increase in the diameter of the well over time is characteristic.

Studies show that the change in the diameter of the well (d) during its drilling depends on the lithological composition of the intersected rocks and their mechanical strength, as well as on the time of exposure of the borehole walls (t) from the moment of overshoot to the moment of recording the cavernogram. The simultaneous consideration of these factors significantly increases the accuracy of the calculation of cavernosity. Therefore, a three-factor correlation was performed. This makes it possible to study the physical and mechanical properties of the rocks of the well section according to the caliper data (BAIBATSHA, 2003; GRIB, 2018).

Results

Figure 2 shows an example of determining the strength of roof rocks and soil of formation $д_6$ continuously through the well section.

To assess the reliability and accuracy of the determinations according to the proposed method, the values of the physical and mechanical properties of rocks obtained using geophysical methods and laboratory methods were compared. Comparisons have shown that discrepancies in the values of the physical and mechanical properties of rocks, determined by the two compared methods, are small (the standard deviation of the mudstones, siltstones, sandstones is, respectively, %: 15,7; 12,5; 13,2) and are within the accuracy of industrial laboratory studies (BAIBATSHA, 2003).

The physical properties of the rocks of the coal-bearing strata of the Karaganda basin are given in the table 2. To establish the nature of the relationship and the mathematical implementation of the relationship established by us, the geophysical parameters of rocks were compared with the results of laboratory determinations of their physical and mechanical properties — the ultimate strength of uniaxial compression (σ_c, MPa) and tension (σ_p, MPa), volume weight (q, g/см^3), porosity (P, %), natural humidity (W, %), based on samples of typical argillites, aleurolites, sandstones of the Dolinskaya and Tentek coal-bearing suites of the basin.

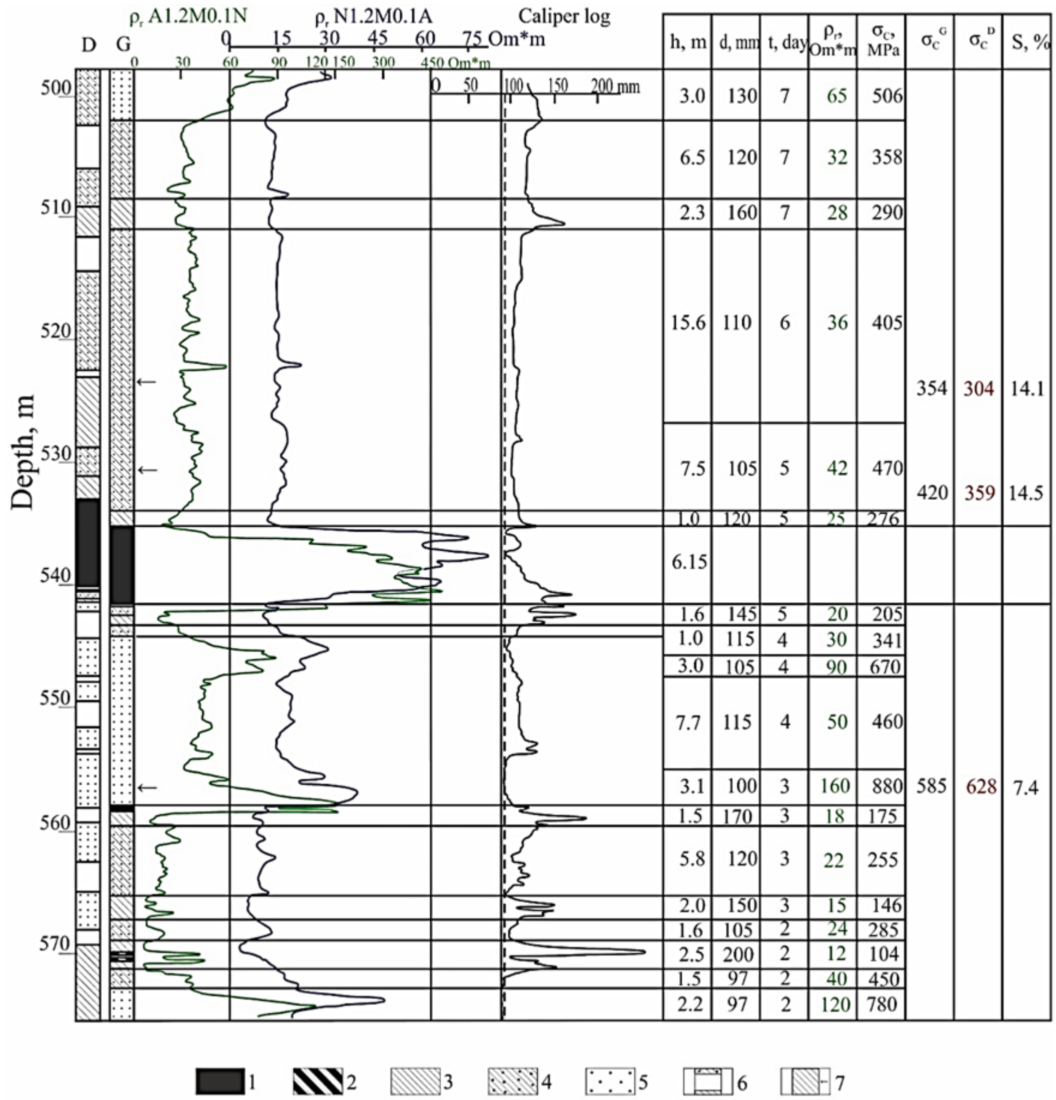

Figure 2 – Determination of the strength of coal-bearing rocks of the Karaganda basin by geophysical methods: 1 – coal, 2 – carbonaceous argillite, 3 – argillite, 4 – aleurolite, 5 – sandstone, 6 – core absent intervals, 7 – sampling point. Lithological column by: D - drilling, G - geophysics.

Table 2 – Values of physical properties of rocks and coals of the Karaganda basin.

Rocks	Age	ρK, Omm	q, g/cm³
Coals	Carboniferous	50-600	1,10-1,60
Carbonaceous argillites	″	20-100	1,30-2,00
Argillites	″	5-30	2,30-2,60
Aleurolites	″	20-60	2,35-2,65
Sandstones	″	30-600	2,40-2,70
Brown coals	Jurassic	40-250	1,10-1,60
Sandy-clay rocks	″	10-60	2,00-2,40
Sandstone conglomerates	″	60-300	2,30-2,55
Clay	Neogene	5-20	2,00-2,30

Mechanical strengths of rocks uniaxial compression and tension can be calculated for each lithotype using the following formulas:

for argillite:

$$\sigma_c = 4.342 d^{-0.33} t^{0.44} \rho_r^{1.042} \qquad R=0.94 \qquad (2)$$

$$\sigma_t = 109.75 d^{-1.29} t^{0.181} \rho_r^{0.603} \qquad R=0.75 \qquad (3)$$

for aleurolites:

$$\sigma_c = 5.658 d^{-0.253} t^{0.013} \rho_r^{0.871} \qquad R=0.87 \qquad (4)$$

$$\sigma_t = 37.21 d^{-1.06} t^{0.13} \rho_r^{0.625} \qquad R=0.70 \qquad (5)$$

for sandstones:

$$\sigma_c = 148{,}33 d^{-0.703} t^{0.10} \rho_r^{0.871} \qquad R=0.83 \qquad (6)$$

$$\sigma_t = 693{,}66 d^{-1.513} t^{0.20} \rho_r^{0.434} \qquad R=0.72 \qquad (7)$$

For a simplified definition of the physical and mechanical properties of rocks, empirical formulas are obtained (2-4) by the method of AR and calipers separately. Relationship of mechanical strength (σ_c) of rocks composing the well section with cavernosity (d, mm) [8], taking into account the recent impact of standing bare walls of the well from the moment of overshoot to cavernometry (t, days) and depth (N, m) It is characterized respectively for argillites, aleurolites and sandstones by equations:

$$\sigma_c^{arg} = 0.4018 * 10^6 d^{-2.362} t^{0.346} H^{0.209} \quad R=0.80 \quad (8)$$

$$\sigma_c^{al} = 3118.0 d^{-1.374} t^{0.088} H^{0.357} \quad R=0.61 \quad (9)$$

$$\sigma_c^{ss} = 5058.7 d^{-1.196} t^{0.188} H^{0.148} \quad R=0.63 \quad (10)$$

Geophysical methods for determining the physical and mechanical properties of rocks that compose well sections are based on the difference in their physical properties, which are an objective characteristic (PENG SUPING, 2007, ZHANG *et al*., 2007, HAO et. al., 2016) and determine the lithological and mineralogical features and the totality of geological processes that the rocks underwent.

Table 3 – Formulas and relations of dependence between geophysical parameters and physicomechanical properties of rocks.

№ п/п	Rock	Equation	Correlation relations
1	Argillite	$\sigma_c = 6{,}87\ p_k^{1.13}$	0,90
2		$\sigma_p = 1{,}02\ p_k^{0.89}$	0,71
3		$P = 38{,}61\ p_k^{-0.39}$	0,68
4		$q = 2{,}27\ p_k^{0.03}$	0,77
5		$W = 21{,}62\ p_k^{-0.53}$	0,53
6	Aleurolite	$\sigma_c = 13{,}38\ p_k^{0.94}$	0,86
7		$\sigma_p = 1{,}17\ p_k^{0.87}$	0,61
8		$P = 38{,}46\ p_k^{-0.38}$	0,46
9		$q = 2{,}17\ p_k^{0.04}$	0,57
10		$W = 12{,}90\ p_k^{-0.41}$	0,43
11	Sandstone	$\sigma_c = 40{,}44\ p_k^{0.62}$	0,80
12		$\sigma_p = 2{,}86\ p_k^{0.65}$	0,61
13		$P = 48{,}86\ p_k^{-0.41}$	0,50
14		$q = 2{,}31\ p_k^{0.02}$	0,61
15		$W = 23{,}25\ p_k^{-0.55}$	0,56

Table 3 shows the formulas and relationships between the geophysical parameters and the physico-mechanical properties of rocks for the Karaganda coal basin.

Argillites are characterized by the lowest values of ρ_K, as well as low strength values (σ_c и σ_p), volume weight (q) and high porosity values (P), natural moisture (W). With the increase of fragments of siltstone increase their ρ_K, σ_c, σ_p, q, on the contrary, P and W decrease. Fine and medium grained sandstones have high values of ρ_K, σ_c, σ_p, [3, 9], q and low values of P, W. Thus, a clear correlation is observed between the physicomechanical properties of rocks and their specific electrical resistances. The direct connection ρ_K has with σ_c, σ_p, q of rocks and the reverse – with their P and W (BAIBATSHA, 2003).

Conclusions

Physical and mechanical properties of rocks are usually determined by core samples by laboratory methods. The main requirement for geological sampling of coal seams and host rocks is to obtain a representative sample, all of which indicators should be adequate to the technological characteristics of coal in the coal seam and the physical and mechanical properties of rocks in the array. However, to ensure these requirements in the process of exploration is not always feasible: incomplete core recovery or lack thereof, selective abrasion, its clogging with rock destruction products, long period of time between sampling and laboratory testing, etc. Geophysical testing, based on the study of the processes of interaction of geophysical fields with rocks, meets the above requirements.

The accuracy of the geophysical methodology for assessing the physical and mechanical properties of rocks fully meets the requirements of practice, in addition, it allows for the determination without sampling cost-effective, quickly, with the greatest completeness of research (it is possible to cover all wells drilled in the explored field). In this case, laboratory research methods should be provided in a small volume as a control of the geophysical method.

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