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ANALYSIS OF EFFICIENCY OF DRILLING OF LARGE-DIAMETER WELLS WITH A PROFILED WING BIT

BADANIA EFEKTYWNOŚCI WIERCENIA STUDNI WIELKOŚREDNICOWYCH ŚWIDREM SKRAWAJĄCYM Z PROFILOWANYMI SKRZYDŁAMI

In Poland all lignite mines are dewatered with the use of large-diameter wells. Drilling of such wells is inefficient owing to the presence of loose Quaternary and Tertiary material and considerable dewatering of rock mass within the open pit area. Difficult geological conditions significantly elongate the time in which large-diameter dewatering wells are drilled, and various drilling complications and break-downs related to the caving may occur.

Obtaining higher drilling rates in large-diameter wells can be achieved only when new cutter bits designs are worked out and rock drillability tests performed for optimum mechanical parameters of drilling technology.

Those tests were performed for a bit ø 1.16 m in separated macroscopically homogeneous layers of similar drillability. Depending on the designed thickness of the drilled layer, there were determined measurement sections from 0.2 to 1.0 m long, and each of the sections was drilled at constant rotary speed and weight on bit values.

Prior to drillability tests, accounting for the technical characteristic of the rig and strength of the string and the cutter bit, there were established limitations for mechanical parameters of drilling technology:

$$P \in (P_{\min}; P_{\max})$$

$$n \in (n_{\min}; n_{\max})$$

where: $P_{\min}; P_{\max}$ – lowest and highest values of weight on bit,
$n_{\min}; n_{\max}$ – lowest and highest values of rotary speed of bit,

For finding the dependence of the rate of penetration on weight on bit and rotary speed of bit various regression models have been analyzed. The most satisfactory results were obtained for the exponential model illustrating the influence of weight on bit and rotary speed of bit on drilling rate. The regression coefficients and statistical parameters prove the good fit of the model to measurement data, presented in tables 4-6.

The average drilling rate for a cutter bit with profiled wings has been described with the form:

$$V_{śr} = Z \cdot P^{a} \cdot n^{b}$$

where: $V_{śr}$ – average drilling rate,
Z – drillability coefficient,

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P – weight on bit,
n – rotary speed of bit,
a – coefficient of influence of weight on bit on drilling rate,
b – coefficient of influence of rotary speed of bit on drilling rate.

Industrial tests were performed for assessing the efficiency of drilling of large-diameter wells with a cutter bit having profiled wings ø 1.16 m according to elaborated model of average rate of drilling. The obtained values of average rate of drilling during industrial tests ranged from 8.33×10^{-4} to 1.94×10^{-3} m/s and were higher than the ones obtained so far, i.e. from 181.21 to 262.11%.

Keywords: drilling wells, cutter bit, dewatering of rock mass, drilling technology

W Polsce wszystkie odkrywkowe kopalnie węgla brunatnego odwadniane są za pomocą studni wielkośrednicowych. Ich wiercenie jest mało efektywne ze względu na występowanie w profilu luźnych utworów czwarto i trzeciorzędowych oraz znaczne odwodnienie górotworu, które jest jedną z głównych przyczyn obwałów ściany otworów i tym samym powstawania trudnych do usunięcia awarii wiertniczych.

W celu uzyskania większych prędkości wiercenia wielkośrednicowych studni odwadniających opracowano nową konstrukcję świdra skrawającego i wykonano w warunkach przemysłowych testy zwiercalności. Testy te wykonano dla świdra o średnicy 1,16 m w wydzielonych warstwach makroskopowo jednorodnych, charakteryzujących się zbliżoną zwieralnością. W zależności od projektowanej miąższości przewiercanej warstwy, wyznaczano odcinki pomiarowe o długości od 0,2 do 1,0 m, a każdy odcinek pomiarowy był wiercony przy stałych wartościach prędkości obrotowej i nacisku osiowego na świder.

Przed przystąpieniem do wykonania testów zwieralności, uwzględniając charakterystykę techniczną urządzenia wiertniczego oraz wytrzymałość przewodu wiertniczego i świdra skrawającego, ustalono ograniczenia na mechaniczne parametry technologii wiercenia w postaci:

$$P \in (P_{\min}; P_{\max})$$

$$n \in (n_{\min}; n_{\max})$$

gdzie: $P_{\min}; P_{\max}$ – najmniejsza i największa wartość nacisku osiowego na świder,
$n_{\min}; n_{\max}$ – najmniejsza i największa wartość prędkości obrotowej świdra,

Dla znalezienia zależności mechanicznej prędkości wiercenia od nacisku osiowego i prędkości obrotowej świdra dla wydzielonych warstw makroskopowo jednorodnych, przeanalizowano różne modele regresyjne. Najbardziej zadawalające wyniki uzyskano dla potęgowego modelu wpływu nacisku osiowego i prędkości obrotowej świdra na prędkość wiercenia. Współczynniki regresji i parametry statystyczne potwierdzające bardzo dobre dopasowanie modelu do danych pomiarowych przedstawiono w tabelach 4-6.

Średnia prędkość wiercenia dla świdra skrawającego z profilowanymi skrzydłami opisana jest wzorem:

$$V_{śr} = Z \cdot P^a \cdot n^b \text{ ; m/s}$$

gdzie: $V_{śr}$ – średnia prędkość wiercenia,
Z – współczynnik zwieralności,
P – nacisk osiowy na świder,
n – prędkość obrotowa świdra.

Dla dokonania oceny efektywności wiercenia wielkośrednicowych studni odwadniających świdrem skrawającym z profilowanymi skrzydłami o średnicy 1,16 według opracowanego modelu średniej prędkości wiercenia wykonano próby przemysłowe. Uzyskane wartości średniej prędkości wiercenia zawierały się w przedziale od $8{,}33 \times 10^{-4}$ do $1{,}94 \times 10^{-3}$ m/s i były wyższe od dotychczas uzyskiwanych od 181,21 do 262,11%.

Słowa kluczowe: wiercenie studni, świder skrawający, odwodnienie górotworu, technologia wiercenia

1. Introduction

In Poland all lignite mines are dewatered with the use of large-diameter wells. Drilling of such wells is inefficient owing to the presence of loose Quaternary and Tertiary material and considerable dewatering of rock mass within the open pit area. Difficult geological conditions significantly elongate the time in which large-diameter dewatering wells are drilled, and various drilling complications and break-downs related to the caving may occur. Moreover, the small drilling rates also elongate the time in which drilling mud affects the near-well zone of the aquifer, thus lowering the hydraulic parameters of the wells and shortening their life.

Obtaining higher drilling rates in large-diameter wells can be achieved only with new cutter bits designs and rock drillability tests performed for optimum mechanical parameters of drilling technology.

2. Influence of drilling technology parameters on drilling rate

The quantitative influence of properties of drilled rocks as well as mechanical, and hydraulic parameters of drilling technology on technical indices of drilling, especially of large-diameter wells, has not been clearly established so far. Among the best described is the influence of weight on bit on the rate of penetration (ROP) both at laboratory and industrial scale (Bourgoyone et al., 1991; Gonet, 1995; Bernt & AAdnov, 1996).

The laboratory experiments carried out on rock blocks revealed both linear and nonlinear character of the dependence of momentous rate of penetration on the weight on bit in the form:

$$v_o = A \cdot P \tag{1}$$

$$v_o = A \cdot (P - P_o) \tag{2}$$

where:

- A — function dependent on rotary speed of bit, physical and mechanical properties of rocks, and hydraulic parameters of well's bottom cleaning.
- P — weight on bit,
- P_o — weight on bit corresponding to the transition from surface to bulk drilling of rock.

However, the exponential character of dependence is most frequently assumed as:

$$v_o = A \cdot P^a \tag{3}$$

where: a — dependence of weight on bit on rate of penetration.

According to the literature data (Gonet et al., 1996), the exponent „a" changes from 0.6 to 2.3.

Another mechanical parameter of drilling technology is the rotary speed of bit. Its influence on the momentous rate of penetration has been recognized relatively well. Theoretical considerations in view (Szostak, 1989; Besson, 1993; Cobb, 1998), the momentous rate of penetration should linearly increase with the growth of rotary speed of bit. However, some studies do not confirm this opinion and the divergence between theoretical and practical results is explained mainly by inefficient cleaning of the well's bottom from cuttings (Uysal, 2011). Basing on literature data (Williams, 1985; Gonet et al., 1996), one can state that the influence of rotary speed of bit is nearly linear to a certain value, after which the momentous ROP plot deflects to the right as a consequence of inefficient removal of cuttings from the well's bottom (Mikaeil et al., 2011). Most of mathematical dependences describing the influence of rotary speed of bit on the rate of drilling, with the remaining parameters constant, assume the following form:

$$v_o = B \cdot n^b \tag{4}$$

where:

- B — function dependent on weight on bit, physical-mechanical properties of rock and hydraulic parameters of well's bottom cleaning,
- n — rotary speed of bit,
- b — coefficient of influence of rotary speed of bit on ROP.

According to literature data (Gonet, 1995), the coefficient b changes from 0.1 to 1.0, depending on the properties of drilled rock.

Generally, the dependence of momentous rate of penetration on mechanical parameters of drilling technology can be described with a general formula:

$$v_o = Z \cdot P^a \cdot n^b \tag{5}$$

where: Z — drillability coefficient.

The drillability factor „Z" describes the system „bit-rock" in the process of drilling rocks, and is always a positive value. Generally, the higher is its value, the easier it is to drill the rock, and so the higher the rate of drilling can be gained (Niżnik & Gonet, 2007).

The momentous rate of drilling value is also significantly influenced by parameters of well's bottom cleaning, i.e. hydraulic properties of drilling mud, design of the hydraulic part and hydraulic parameters of well's bottom cleaning (Williams, 1985; Wiśniowski et al., 2007). The investigations revealed that the increase of density of drilling mud, solids content in drilling mud, dispersion level and kinematic viscosity cause reduction of the rate of drilling. The drilling rate increases with the growth of drilling mud filtration.

3. Analysis of drilling with profiled wing bits

The major technical problem related to drilling large diameter dewatering wells in lignite mines lies in obtaining relatively high rates of penetration, thanks to which the time of operation of drilling mud on the rocks in the near-well zone can be shortened, the stability of the well's walls improved and the number of drilling failures reduced.

Among the most important factors affecting high rates of penetration are the correct selection of the bit-type and use of optimum mechanical and hydraulic parameters of drilling technology (Miska, 1975, Macuda, 1995).

In Poland, the large-diameter wells are drilled with the use of cutter and cone bits. However, cutter bits are mainly used for drilling wells in loose or low-compact Quaternary and Tertiary strata, as their price is low, they are easy to handle and the technical-economic indices of drilling are favorable.

To increase the rate of drilling of large-diameter dewatering wells, a new cutter bit with profiled wings was designed (fig. 1) (Gonet et al., 1996).

Fig. 1. Large-diameter cutter bit with profiled wings ø 1.16 m

The performing of a prototype cutter bit ø 1.16 m was followed by drillability tests on dewatering wells in the field Bełchatów. The wells were performed with a rig Wirth B3A.

The optimum mechanical parameters of drilling technology were established on the basis of drillability tests, which in turn, were based on the following assumptions:

- bit cycle in macroscopically homogeneous rocks,
- bit type correctly selected for the given type of drilled rock,
- weight on bit and its rotary speed have constant values,
- weight on bit and rotary speed belong to a set of admissible decisions, resulting from the technical characteristic of the rig.

For drillability tests performed in the geological profile in the field Bełchatów there were selected macroscopically homogeneous layers, i.e. having similar drillability for a definite kind and type of bit. This issue is important for the selection of optimum drilling technology parameters; the change of lithology of drilled rocks does not have be related with a change in their drillability, and rocks having the same label may differ in their drillability.

Basing on literature data (Kidybiński, 1982; Wiłun, 2003) the following macroscopically homogeneous layers have been distinguished in the entire profile:

W_1 – sands, gravel,
W_2 – lignite, coal clays,
W_3 – clays, clayey mudstones,
W_4 – marls,
W_5 – limestone, limestone rabbles,
W_6 – limestones with quartzite inserts.

Layers $W_1 \div W_3$ represent Quaternary and Tertiary beds, whereas the remaining ones $W_4 \div W_6$ represent Mesozoic strata.

Prior to drillability tests, accounting for the technical characteristic of the rig Wirth B3A and strength of the string and the wing bit, there were established limitations for mechanical parameters of drilling technology:

$$P \in (P_{min}; P_{max}) \tag{6}$$

$$n \in (n_{min}; n_{max}) \tag{7}$$

where:

$P_{min}; P_{max}$ — lowest and highest values of weight on bit,
$n_{min}; n_{max}$ — lowest and highest values of rotary speed of bit,

Next, within the assumed limitations (6) and (7) there were established five measurement points with which the sections of the well were drilled (fig. 2).

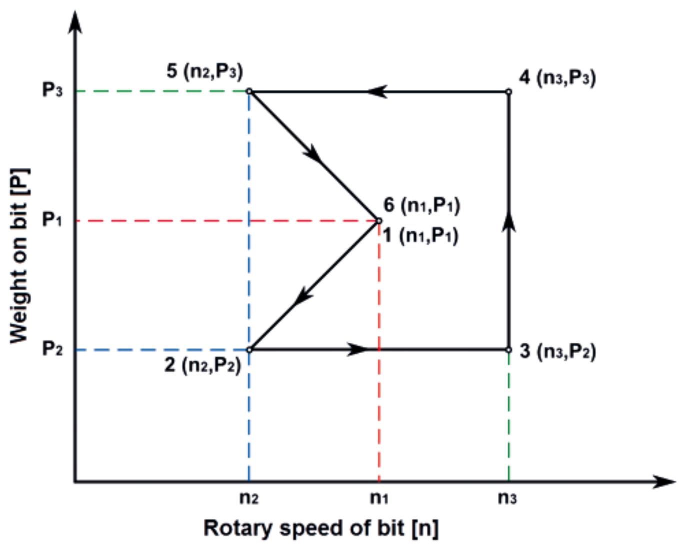

Fig. 2. Scheme of drillability test

Each time the end point of the drillability test corresponded with the initial point to check out whether or not the wells were drilled in the same macroscopically homogeneous layers. It has been assumed that the well was drilled in the same conditions if the drilling rate at points 1 and 6 did not differ more than by 10-15%.

The drillability tests with the newly designed bit ø 1.16 m were conducted for the following drilling technology parameters:

- weight on bit $1.47 - 2.45 \cdot 10^4$ N,
- rotary speed of bit $0.25 - 1.0$ s^{-1},
- volumetric stream of drilling mud 0.077 m^3/s,
- drilling mud flow rate inside string 4.3 m/s.

Depending on the designed thickness of drilled layer, there were determined measurement sections 0.2; 0.3; 0.4; 0.5 and 1.0 m long. Each section was drilled at constant values of rotary speed and weight on bit.

The drillability tests were performed in the course of drilling operations on dewatering wells No. 86A-1, 89C, 128K, C4, PP-343, PP-344, PP-345 in the field with the use of a rig Wirth B3A.

4. Results and discussion

For finding the dependence of the rate of penetration on weight on bit and rotary speed of bit for selected layers W_1, W_2 and W_3, various regression models have been analyzed (Chatfield & Collins, 1980; Bates & Watts, 1984; Dobosz, 2001). The most satisfactory results were obtained for the exponential model illustrating the influence of weight on bit and rotary speed of bit on drilling rate. The regression coefficients and statistical parameters prove that the model well fits the measurement data, as presented in tables 4-6.

The average drilling rate for a cutter bit with profiled wings has been described with the form:

$$V_{śr} = Z \cdot P^a \cdot n^b \tag{8}$$

where:

$V_{śr}$ — average drilling rate,
Z — drillability coefficient,
P — weight on bit,
n — rotary speed of bit,
a — coefficient of influence of weight on bit on drilling rate,
b — coefficient of influence of rotary speed of bit on drilling rate,

To analyze the exponential model representing the influence of weight on bit on the rotary speed of bit, a logarithm was found in equation 8 (at sides) and the result was transformed into a linear equation

$$\ln V = \ln Z + a \cdot \ln P + b \cdot \ln n \tag{9}$$

The regression coefficients for model 9 and their statistical significance were calculated with the use of software STATISTICA 8 – multiple regression module (Chatfield & Collins, 1980; Stanisz, 2007).

The most important parameter determining the good fit of the model is coefficient of determination R^2. This coefficient measures which part of the general dependent variability is explained by regression and assumed values from 0 to 1. The closer is value R^2 to unity, the better fitting of the model. As in all analyzed cases it is above 0.9 and the number of measurements (60 to 62) is incomparably higher than the number of dependent variables (2), the model can be assumed to have a good fit.

In the statistical analysis there was also given corrected coefficient R^2, which determines the fit of regression equation to other sample of the same population. Its value is always lower than R^2.

The presented statistics F was used for verifying the hypothesis that regression coefficient was not equal to 0.

The error of model estimation defines by what value the constant may differ from the calculated one.

Tables 1 to 3 contain both coefficients of average rate of penetration and also parameters verifying the statistical correctness of the model:

- population of samples,
- standard error of regression coefficient,
- *t* Student value for specific regression coefficients,
- significance levels for specific regression coefficients,
- coefficient of multiple correlation R,
- coefficient of determination R^2,
- corrected coefficient of determination R^2
- Fisher-Snedecor F statistics and significance level p,
- standard error of estimation.

TABLE 1

Parameters of equation of average rate of penetration with cutter bit having profiled wings ø 1.16 m in layers W_1

Determinant parameter	**Regression coefficient**	**Standard error of regression coeff.**	**Value of *t* Student test**	**Significance level**
Free expression ln Z	–14.5729	0.367252	–39.6809	0.000000
a	0.8388	0.037475	22.3829	0.000000
b	0.6573	0.028368	23.1689	0.000000
Number of measurements $N = 62$ Free expression $Z = 4.68888 \cdot 10^{-7}$ $R = 0.97031249$ $R^2 = 0.94150633$ Coefficient of determination $R^2 = 0.93952349$ Fisher-Snedecor statistics $F(2.59) = 474.83$ $p < 0.0000$ Standard error of estimation = 0.06404				

TABLE 2

Parameters of equation of average rate of penetration with cutter bit having profiled wings ø 1.16 m in layers W_2

Determinant parameter	Regression coefficient	Standard error of regression coeff.	Value of *t* Student test	Significance level
Free expression ln *Z*	–15.5731	0.442615	–35.1843	0.000000
a	0.9171	0.044613	20.5572	0.000000
b	0.6785	0.045987	14.7546	0.000000
Number of measurements $N = 60$ Free expression $Z = 1.72460 \cdot 10^{-7}$ $R = 0.96047983$ $R^2 = 0.92252151$ Coefficient of determination $R^2 = 0.91980297$ Fisher-Snedecor statistics $F(2.57) = 339.34$ $p < 0.0000$ Standard error of estimation = 0.10525				

TABLE 3

Parameters of equation of average rate of penetration with cutter bit having profiled wings ø 1.16 m in layers W_3

Determinant parameter	Regression coefficient	Standard error of regression coeff.	Value of *t* Student test	Significance level
Free expression ln *Z*	–16.6752	0.343409	–48.5580	0.000000
a	1.0257	0.035214	29.1275	0.000000
b	0.6700	0.029064	23.0531	0.000000
Number of measurements $N = 60$ Free expression $Z = 5.72865 \cdot 10^{-8}$ $R = 0.97702276$ $R^2 = 0.95457348$ Coefficient of determination $R^2 = 0.95297957$ Fisher-Snedecor statistics $F(2.57) = 598.89$ $p < 0.0000$ Standard error of estimation = 0.05770				

The coefficients of model illustrating the average drilling rates *a*, *b* and *Z* for selected macroscopically homogenous layers W_1, W_2 and W_3 have been presented in table 4.

TABLE 4

Values of coefficients Z, a and b for a model of average drilling rate with cutter bits having profiled wings

Diameter of bit m	Type of macroscopically homogeneous layer	Coefficients		
		Z	***a***	***b***
1.16	W_1	$4.68888 \cdot 10^{-7}$	0.8388	0.6573
	W_2	$1.72460 \cdot 10^{-7}$	0.9171	0.6785
	W_3	$5.72865 \cdot 10^{-7}$	1.0257	0.6700

Industrial tests were performed for assessing the efficiency of drilling of large-diameter wells with a cutter bit having profiled wings ø 1.16 m according to elaborated model of average rate of drilling. In the course of drilling the well with the rig Wirth B3A, the following technological parameters were used, depending on the type of drilled rock mass:

- inner diameter of string 0.145 m,
- weight on bit $1.47 – 2.94 \cdot 10^4$ N,
- rotary speed of bit $0.25 – 1.0\ s^{-1}$,
- volumetric stream of drilling mud $0.077\ m^3/s$,
- flow rate of drilling mud inside the string 4.3 m/s.

The obtained values of average rate of drilling during industrial tests ranged from 8.33×10^{-4} to 1.94×10^{-3} m/s and were higher than the ones obtained so far, i.e. from 181.21 to 262.11%.

4. Conclusions

The average rate drilling model for cutter bits with profiled wings may help increase the efficiency of drilling of large-diameter dewatering wells in difficult geological conditions.

In the industrial practice the selection of optimum mechanical parameters of drilling technology must be realized in view of limitations resulting from weight on bit and rotary speed of bit.

When using cutter bits, especially the large diameter ones, additional limitations resulting from the technical characteristic of the rig and string should be taken into account, i.e. admissible turning moment and power.

The computer software, a scheme of which has been presented in the paper, has been worked out for fast and accurate programming of optimum values of weight on bit and rotary speed of cutter bit in view of minimum unit cost of drilling a well.

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