EXPERIMENTAL RESEARCHES REGARDING THE DRILLING PROCESS OF THE MINE SHAFTS BY MEANS OF SURFACE INSTALLATIONS

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ABSTRACT. In order to realize in economic conditions aerating and exploitation mine shafts of coal, iron ore, bituminous schist and petroleum from depleted reservoirs, were built in Romania drilling rigs for large diameters ranging between 72 inches (1.83 m) and 245 inches (6.223 m). All these are using the technology of rotary drilling with hydrostatic transmission, drill column and with reverse circulation of drilling fluid and airlift. In the paper the determinant factors of the drilling process of large diameter and the accompanying phenomena, which characterize its specific dynamics are presented. The technological and technical problems (the last ones concerning the hydrostatic driving system, durability and implicitly construction of bit and drill pipe), which appeared in practice of the exploitation of these drilling rigs, imposed an experimental approach of drilling process in field conditions. In this way, in the paper are shown the experiment conditions in case of drilling a mine shaft having a diameter of 142.5 inches (3.62 m) and the methodological aspects of experimental electrical strain-gauges investigation by using some stress captors designed with this end in view, a collector with sliding contacts having unusual sizes adjusted to type-size of the drill pipe of 10¾ inches and a recording appliance in real-time. Also, some recordings are presented and pointed out by means of some diagrams and empirical formulas, a series of dependences among the physical sizes which define the drilling process: the weight on bit, the drilling torque, the rotational speed and the power and moment of friction between the drilling column and the drilling fluid. The obtained results have been already used in the practice of big holes drilling, for improving the drill pipe construction, in design of hydrostatic driving of the rotary table and in simulation the drilling process.

ИЗСЛЕДВАНИЯ ОТНОСНО ТЕХНОЛОГИИТЕ ЗА СОНДАЖНО ПРОКАРВАНЕ НА ВЕТРИКАЛНИ ШАХТИ

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РЕЗЮМЕ. За да се осъществи вентилация в условия на икономичен режим и проучване на минните шахти на въглища, желязна руда, асфалтови шисти и нефт от изчерпани минни басейни в Румъния бяха изградени сондажни пръстени с голям диаметър, вариращи между 72 инчове (1.83 m) и 245 инча (6.223 м). Всички те използват технологията на ротационното пробиване с хидростатична трансмисия, колонкова пробивна машина и с обратна циркулация на сондажния разтвор и въздушен пренос. В статията са представени определящите факторите при технология на сондаж с голям диаметър и придружаващите го явления, които характеризират неговата специфична динамика. Технологичните и технически проблеми (някои от които, се отнасят до работата на хидростатичната система, стабилността на част от изградения сондаж и тръбопроводна празнина), които се появиха на практика при разработването на тези сондажни съоръжения, наложиха експериментален подход на сондажния процеса в полеви условия. По този начин, в статията са описани експерименталните условия в случай на сондиране на минна шахта, имаща диаметър от 142.5 инча (3.62 m) и методологичните аспекти на експерименталното проучване на инструменти за измерване на електрическото напрежение чрез използване на някои предварително уловени стойности на напрежението, колектор с плъзгащи се връзки имащи големи размери, приспособени към размера на сондажната помпа от 10¾ инча и записващо устройство в реално време. Освен това са представени и някои от регистрираните данни, отразени на няколко диаграми и емпирични формули, серия от зависимости, които дефинират сондажния процес: теглото, сонданото усукване, скоростта на ротация и силата и триещия момент на между сондажната колона и сандажната течност. Получените резултати бяха вече използувани в практиката на пробиване на големи сондажни дупки, за подобряване конструкцията на сондажния тръбопровод, в проектирането на хидростатичното сондиране на въртящ се постамент и при имитация на пробивен процес.

Introduction

For drilling aerating and recovery mine shafts, large diameter drilling rigs (LDDR) may be used, by means of surface driving, with rotary entrainment of bit (B) by means a drilling string (DStr) and reverse circulation by airlift (A-L) of the drilling fluid (DF). The drilling process (DPr) is the result of conjugated action of rotational motion of the bit rollers (BRo) in contact with the rock and of the drilling fluid running between the bit surface and the borehole bottom (BHB) with horizontal velocity ($v_{h.\,DF}$), and inside the drilling string with ascension velocity (v_a), for removing the rock fragments on the surface. The two types of motion are separately produced: the rotational motion appears being transmitted in the frame of a rotary system (RS) and the drilling fluid running is a result of some pump upsetting and lifting by compressed air produced by compressors. According to its physical properties — density (ρ_{DF}), viscosity (v_{DF}), filtration etc. — the drilling fluid running will ensure the shaft wall stability, creates a hydrostatic pressure (p_{Hs}) on the hole bottom, contributes to the kinetic energy dissipation of the drilling string, and due to its running parameters — to pressure and flow (Q_{DF}) — cleans the hole bottom of detritus. The determinant action in drilling process is represented by the differential pressure between the drilling fluid and the borehole bottom ($\Delta p_{DF\text{-}BHB}$) and the impact forces of the roller teeth (F_{RoT}) on the rock, forces of crushing and cutting, produced by bit rotational motion, subjected to pressure force (F_B) and influenced by the washing degree of the bit rollers and the

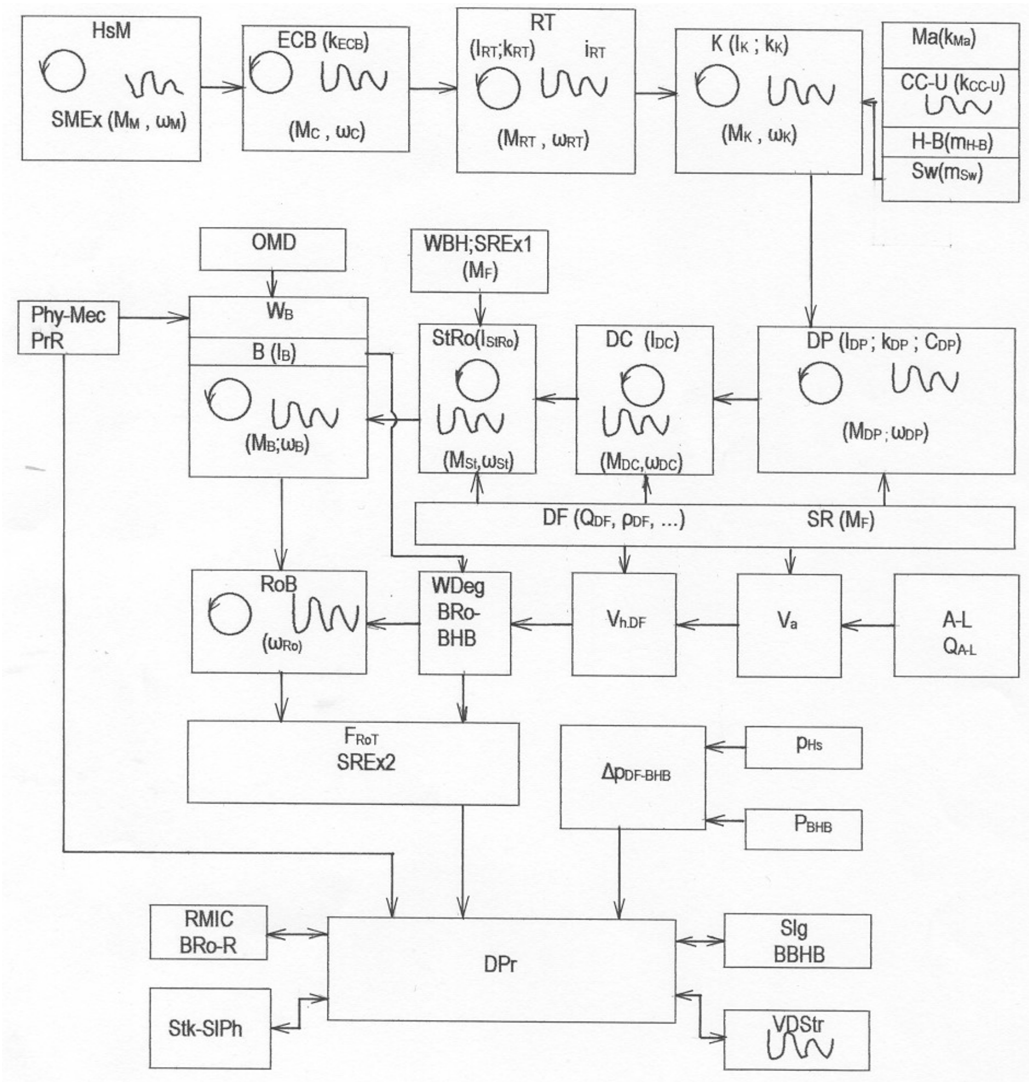

Fig. 1. The block-scheme of the determinant factors of the large- diameter drilling process and the accompanying and influencing phenomena: HsM — hydrostatic motors; SMEx — source of motive excitation; M— rotation moment; ω — angular speed; ECB — elastic coupling with bolts; k — elasticity constant; RT — rotary table; I — mass moment of inertia; i_{RT} — transmission ratio of the rotary table; K — kelly; Ma — mast; CC-U — cable coiling-up between crown-block and hook-block; H-B — hook-block; m — mass; Sw — swivel; DP— drill pipes; C — viscous damping coefficient; DC — drill collars; StRo — stabilizer with rollers; WBH — wall of the borehole; SREx — source of reaction excitation; DF — drilling fluid; SR — soft reaction; M_F— friction moment; B — bit; W_B— weight-on-bit; Phy-MecPrR — physico-mechanical properties of the rocks; OMD — operating mode of the driller; RoB — rollers of the bit; WDegRo-BHB — washing degree of the bit rollers and the borehole bottom; A-L — airlift; Q_{A-L}— flow of the airlift; v_a — ascension velocity; $v_{h.DF}$ — horizontal velocity of the drilling fluid; F_{RoT} — impact forces of the bit roller teeth on the rock; Δp_{DF-BHB} — differential pressure between the drilling fluid and the borehole bottom; DPr — drilling process; RMICBRo-R — rotary movement with intermittent contact between the bit rollers and rock; Stk-SlPh — stick-slip phenomenon; SlgBBHB — sloughing of the bit and the borehole bottom; VDStr — vibrations of the drill string.

borehole bottom (WDegBRo-BHB). In this way, the main working system in the drilling process is the rotary system of the drilling rig, which must be considered as a dynamic system, having a certain structure with fundamental properties — inertial (I), elastic (k) and dissipative properties — on which motive actions and reactions are applied, determining its non-steady-state motion, characterized by a variable angular speed (ω). In case of downward drilling rigs, of surface, the motive action is usually carried out by hydrostatic motors (HsM), the main reaction proceeds from the bottom hole rock contacting the bit, but the other reactions proceed from the wall of the borehole (WBH) which comes in contact with the stabilizer rollers and from drilling fluid running round the drill string. Therefore, three sources of dynamic excitation are noticeable producing and influencing the motion of the rotary system: the source of motive excitation (SMEx) represented by hydrostatic motors and the two sources of reaction excitation (SREx) or„hard" reactions due to the contact between the stabilizer rollers and the shaft wall (SREx1), and between the bit rollers and the rock (SREx2). SREx2 has a random character determined by the variation of the rock physico-mechanical properties. The reaction of the drilling fluid on the drill string, which is subjected to a rotational motion, is characterized as a „soft" reaction (SR) with a dissipative effect, but not exciting one.

Being agreed with this conception of integrality „rotary system-rock-drilling fluid-wall of the borehole" („RS-R-DF-

WBH"), the determinant factors of the large-diameter drilling process and the accompanying and influencing phenomena are pointed out in Fig. 1. Due to the main dynamic properties of the whole rotary system, to the elasticity (k_{CC-U}) of the cable coiling-up (CC-U) between the crown-block and hook-block, to existence of the dynamic excitation-sources, to the technical and technological particularities of the large-diameter drilling in comparison to that of a normal diameter and to variation of the drilling mechanical parameters (W_B, M_B and ω_B), the drilling process of the mine-shafts is pre-eminently a dynamic and vibrating process. It is accompanied and its efficiency is influenced by phenomena as: sloughing of the bit and the borehole bottom (SlBBHB), torsional, axial and bending vibrations (V) (overlaid to dynamic actions of the same type) of the drill string (Vlad and Parepa, 1989), rotary movement with intermittent contact between the bit rollers and the rock (RMICBRo-R) and stick-slip phenomenon (Stk-SlPh) (Parepa, 2001). The harmful effects on the bit rollers and drill pipes and on the hydrostatic transmissions were ascertained and imposed performing some experimental studies in site conditions (see also Parepa, 2001).

Experimental conditions

The dynamic measurements were made during the drilling of a mine shaft having a diameter of 3.62 m for mining works and technological experiments within of the petroliferous structure from Buştenari, with the view of its exploitation by underground gravitational drainage from the depth of 326 m. The drilling was carried out by using a drilling rig F320-3DH-M equipped with two electro-hydrostatic driving groups and a drill sting with drill pipes of 10¾ inches, multiple-roller bit, roller-type stabilizer and a drill collar made of steel-casting annular sleeves („doughnut weights") with a diameter of 1.4 meters. During the measurements, a structure belonging to Oligocene medium was passed through, made from clay and gray marl, sometimes being schistose, sandy marl containing centimeter interpolations of pozzolana and decimeter interpolations from sands and sandstones with collecting properties, and having a hardness of ST4. A drilling method was applied, characterized by a weight-on-bit (W_B) with measures in the range [15; 210] kN, rotary speed of the kelly (n_K) with mean measures in the range of [5; 12] rot/min, density of the drilling fluid (ρ_{DF}) of 1.19 t/m^3, flow of the drilling fluid (Q_{DF}) between 90 and 100 l/s, airlift flow (Q_{A-L}) of 60 m^{3}N/min and a pressure (p_{A-L}) of 0.6 MPa.

The strain-measuring chain is made from stress captors (SC), placed in the drill string, a collector with sliding contacts (CSG), placed on the upper part of the drill string, and a dynamic recording electronic system. The stress captors were built of drill pipes having zones where strain gauges were applied, protected by special coatings (Fig. 2). The collector with sliding contacts (Fig. 3), with an outside diameter of the rings of 537 mm, was designed for its assembling on the upper drill pipe of 10¾ inches in order to transmit the electrical signals from strain-gauge bridges of measuring of the torsion and axial strain (of the force and bending moment), of the whole strain and strains from zones with stress concentrators of the drill pipes. The technology of its carrying out represents the solving of a singular and, at the same time, a difficult problem.

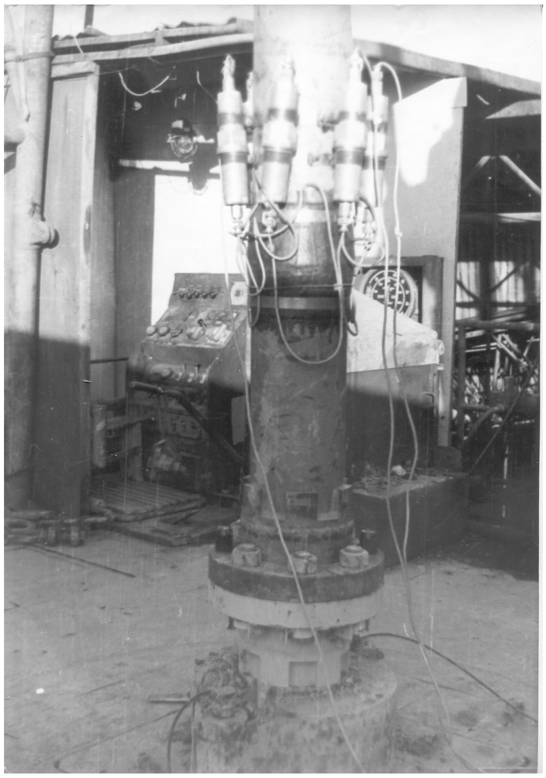

Fig. 2. Stress captor assembled in the drill string, before lowering in the shaft.

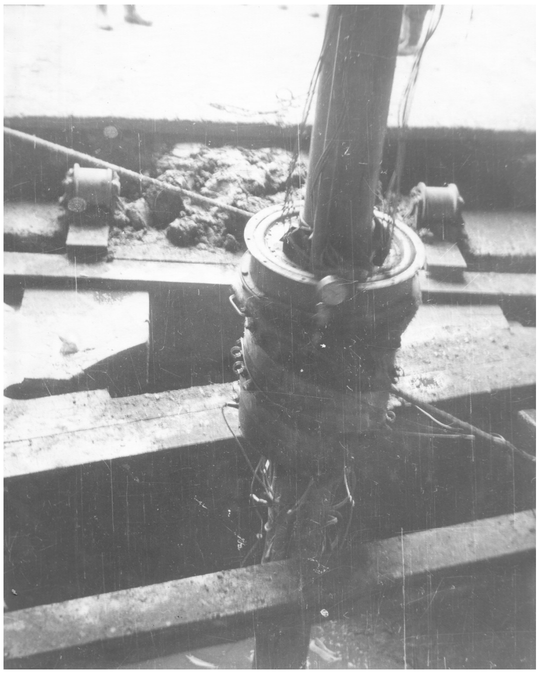

Fig. 3. Collector of sliding contacts (CSC), placed on the upper drill pipe of 10¾ inches with airlift pipes.

Experimental results

The drilling process, as a dynamic and vibrating process, may be characterized by the dynamic responses (DR) of the stress captors. Recordings were carried out during the free rotation of the drill string and during the drilling in two cases of the rotary table working: with a hydrostatic generator (HdG) and two generators.

During the free rotation, the dissipative action of the drill string rotation energy takes place, produced by the drilling fluid, which is presented in Figs. 4 and 5, separately on the component elements (DP, DC, B+St) and for the whole drill string, and also the exciting reaction of the shaft wall in contact with the stabilizer, by oscillation amplitude spectrum of the friction moment (M_F), according to Fig. 6

The diagrams in Figs. 4 and 5 show a greater influence of the bit diameter and stabilizer as against that of length of drill pipe assembly on the friction moment (M_F) and power (P_F). The friction power may be expressed by the empirical relationship:

$$P_F = 58{,}243\cdot 10^{-3}\cdot \rho_{DF}\cdot \omega_K^{1,85}\cdot \sum_{i=1}^{3} L_i\cdot D_i^2, \qquad (1)$$

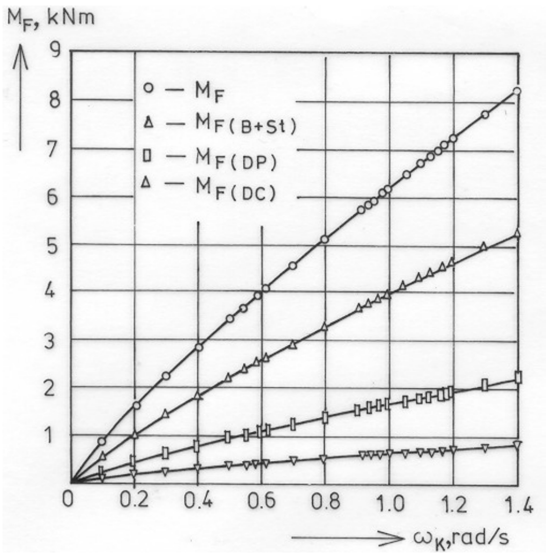

Fig. 4. The diagram of variation of the total friction moment (M_F) and among the drill string elements and the drilling fluid and the shaft wall ($M_{F(B+St)}$, $M_{F(DP)}$, $M_{F(DC)}$) dependent on the angular speed of the kelly (ω_K).

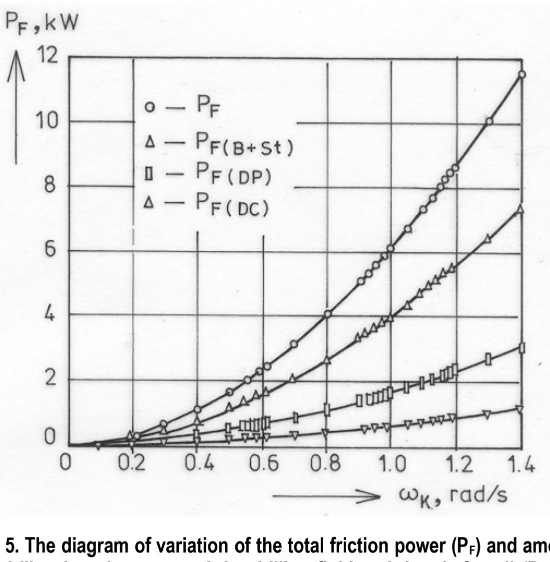

Fig. 5. The diagram of variation of the total friction power (P_F) and among the drill string elements and the drilling fluid and the shaft wall ($P_{F(B+St)}$, $P_{F(DP)}$, $P_{F(DC)}$) dependent on the angular speed of the kelly (ω_K).

where L_i and D_i, $I=\overline{1,3}$, represent the length and diameter, respectively of the drill pipes (DP), drill collar (DC) and the bit-stabilizer assembly (B+St); ρ_{DF} — density of the drilling fluid; ω_K — angular speed of the kelly (K), these size having the following measure units: $[L_i]=[D_i]=m$, $[\rho_{DF}]=t/m^3$, $[\omega_K]=rad/s$, $[P_F]=kW$.

In the case of low rotational speeds, when a single hydrostatic generator works, may be found that oscillations with higher amplitudes are produced than in case of high rotational speeds, when two hydrostatic generators work. In this way, in the first case the maximal and minimal deviations are 26.9%, -26.2% respectively from the average value ($M_{F.0}$) of 3.99 kNm, and the most important energetic contributions in the oscillation process has the main harmonic followed by a harmonic of second order, with a share of 12.8% from the contribution of the main harmonic (Fig. 6). In this way may be written:

$$M_F \cong M_{F.0} + \sum_{j=1}^{2} M_{F.j}\cdot \sin\left(j\cdot\omega_0 - \varphi_j\right), \qquad (2)$$

where $M_{F.1}$=0.614 kNm; $M_{F.2}$=0.217 kNm; ω_0=0.597 rad/s; φ_1=0.024 rad; φ_2=0.015 rad. In case of two times increase of the drill string driving rotational speed, an increase of 1.8 times of $M_{F.0}$ is noticed (Fig. 6).

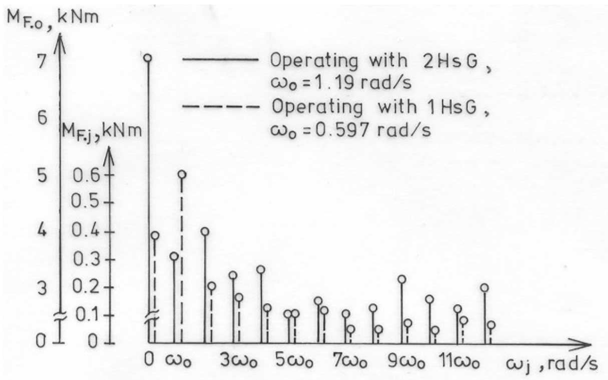

Fig. 6. Spectrum of oscillation amplitudes of the friction moment between the stabilizer rollers and the shaft wall.

During the drilling with different values of the weight-on-bit (W_B), dynamic responses having the shape of those presented in Figs. 7 and 8, were obtained. These figures show the character of the kelly rotation moment (M_K) and angular speed (ω_K) variation, of the weight-on-bit (W_B) variation, and of the axial force (F), torsion moment (M_T) and bending moment (M_{Bend}) variation which act on the drilling pipes in different their sections. In this way, M_K and M_T have an oscillating character whit an equal period to that of a complete rotation, ω_K has a variation of the same type, but in inverse sense that those of M_K. W_B and F present a random character, having higher frequencies than M_K and M_T. For example, for W_B=27 kNm and n_K=7 rot/min, M_K is described by a variation of shape (2) where $M_{K.0}$=14 kNm, on which the main harmonic (with $M_{K.1}$=-1.73 kNm, ω_0=0.743 rad/s and φ_1=-0.022 rad) and harmonic of order 23 (with $M_{K.23}$=-0.304 kNm and φ_{23}=0.024 rad) are superposed, variation of these oscillations being of about 29%

from the mean value, showing the existence of a stick-slip motion of the bit (in accordance to Rappold, 1993). This phenomenon appears in case of working with a single hydrostatic generator, when the rotational speed is of 5÷7 rot/min and when W_B has higher values. In case of drilling with two hydrostatic generators, the oscillating process of the drill string is intensified. The same, in case of W_B values exceeding 130 kN in soft rocks, the sloughing of the bit and its irregular pronounced motion, with momentary or some seconds blockings are ascertained, which are specific to stick-slip phenomenon, requiring a W_B reduction and even the raising of the bit from the borehole bottom. In formations with sandstone and pozzolana content, which impose greater values of W_B, dislocations of big fragments of rock are produced, which are difficult to be brought to the surface, and are accompanied by great vibrations and noises (also due to the rock hitting at the inside wall of the drill pipes) and by increase of oscillation amplitudes of the bending moment, acting on the drill pipes, and by its tendency to become alternating-symmetrical.

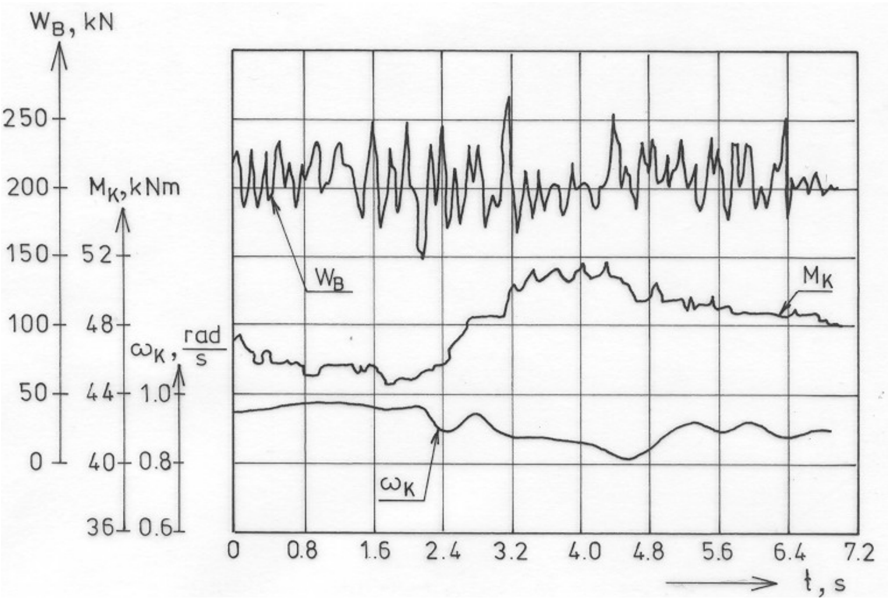

Fig. 7. Variation of the weight-on-bit (W_B), of the kelly rotation moment (M_K) and of its angular speed (ω_K) during a complete rotation, according to recording no. 22.2.

It is interesting to be pointed out the fact that the bending stress variability gives the equivalent stress (σ_{Eqv}) variation character in the cross-section of the drill pipes (Fig. 8).

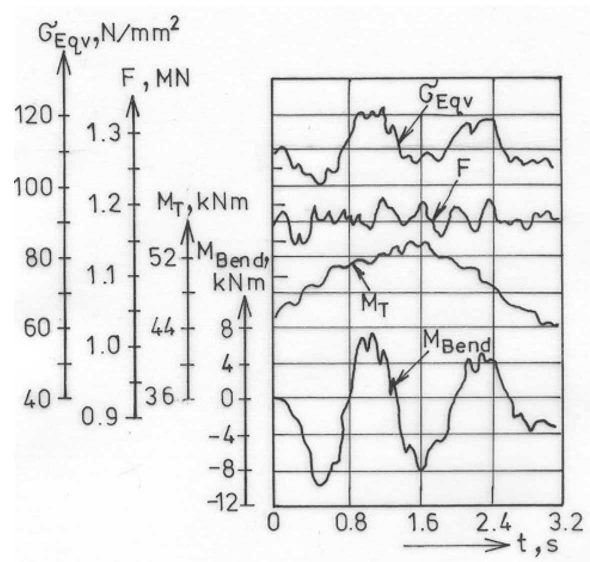

Fig. 8. Variation of the tensile force (F), of the torsion moment (M_T), of the bending moment (M_{Bend}) and of the equivalent stress (σ_{Eqv}) in a cross-section of the drill string during of a half rotation, in the case: W_B=130 kN; ω_K=1.007 rad/s.

The recording processing like that in Fig. 7 led to the diagrams M_B=f(W_B), ω_B=f(W_B) and ω_K=f(M_K) presented in Figs. 9, 10 and 11 which are basic to stipulate the following empirical formulas:

$$M_B = 4{,}831 \cdot 10^3 \cdot c_D \cdot D_B \cdot W_B^{0{,}547}, \qquad (3)$$

where D_B is the bit diameter and c_D — the drillability coefficient, according to E. A. Morlan;

$$\omega_B = 0{,}842 + \frac{0{,}346}{1 + \left(W_B / 132{,}8\right)^{3{,}437}}; \qquad (4)$$

$$\omega_K = 0{,}897 + \frac{0{,}296}{1 + \left(M_K / 37{,}105\right)^{11{,}944}}. \qquad (5)$$

In this relationships, which are valuable for working by means of two hydrostatic generators, the measuring units are: [D_B]=m; [W_B]=kN; [ω_B]=[ω_K]= rad/s; [M_B]=[M_K]=kNm.

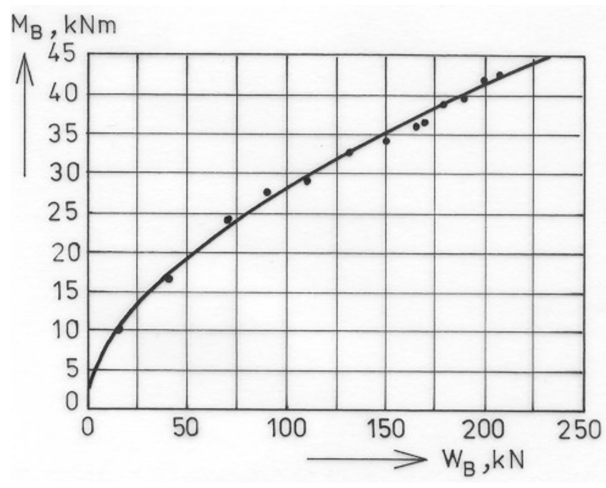

Fig. 9. The rotation moment of the bit (M_B) dependent on weight-on-bit (W_B).

Conclusions

The experimental research results carried out in the field and analysis presented in Introduction demonstrate the importance of the weight-on-bit (W_B), of the Kelly rotary speed (n_K), of the bottom hole washing conditions (determined by Q_{DF}, Q_{A-L}, by the bit construction and of its rollers, and of their position on the bit face) on the drilling process, all of them must be according to the physico-mechanical properties of the rocks. These factors and excitation sources, especially which are of „strong" reactions, and with the main dynamic properties of the drilling equipment elements characterize the drilling process of the mine shafts as a dynamic and vibrating process, accompanied by phenomena influencing its efficiency and durability of the bit rollers, drill pipes and even driving groups.

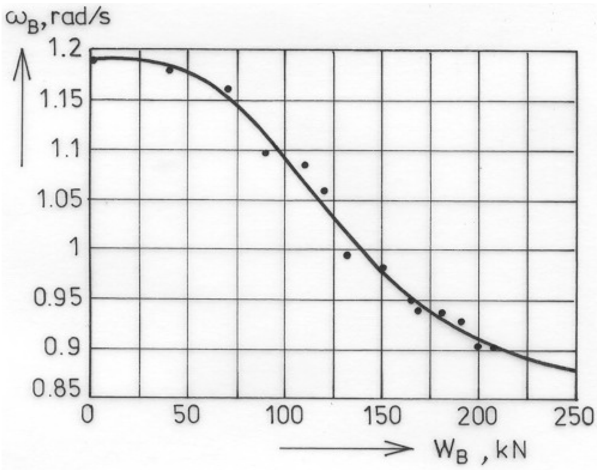

Fig. 10. The angular speed of the bit (ω_B) dependent on weight-on-bit (W_B).

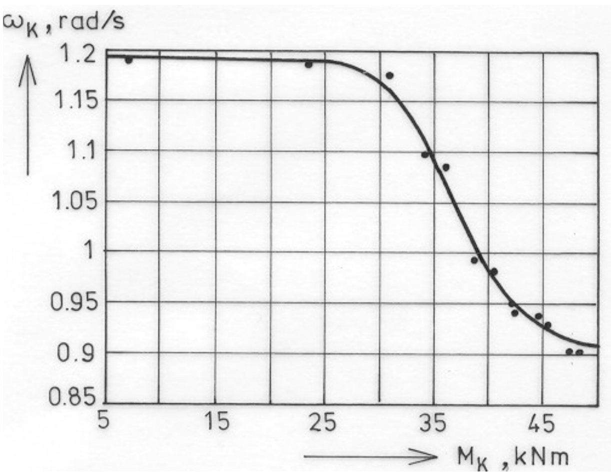

Fig. 11. The angular speed of the kelly (ω_K) dependent on its rotation moment (M_K).

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The dynamic responses of the stress captors placed in the drill string of 10¾ inches, point out the variable character of the weight-on-bit, of the rotation moment, of the friction moment between the drill string and drilling fluid, and between the stabilizer rollers and the shaft wall, and also the variation of the dynamic action on the drill pipes (of the tensile force, torsion moment and bending moment). At the same time, these recordings catch phenomena which accompany the drilling process: sloughing of the bit and the borehole bottom, the motion of intermittent contact of the bit rollers with the shaft bottom, the stick-slip bit phenomenon and drill string vibrations. The variation law of the equivalent stress in the drill pipe's cross-section, in a complete rotation, shows the main influence of the flexural oscillations on it.

Establishment in this work of dependences among different specific physical sizes of the drilling process by using empirical formulas points out the followings: the real appreciation of friction between the drill string components and drilling fluid and its contribution at total resistance moment that must be overcame during the drilling; specification of the bit diameter and the drill string length influence on the friction moment and power; a more correct estimation of W_B influence on M_B, in stated drilling conditions, with $W_B \in$ [15; 210] kN, by means of the relationship (3) compared to E. A. Morlan's formula; estimation of the bit rotary speed dependence on W_B and on M_K, determined by the functional characteristic of the electro-hydrostatic driving group and on the interaction rotary system-rock.

The obtained results have been already used for improving the bit construction, the drill pipes and the hydrostatic transmission construction, and for efficiency rising of the big-diameter drilling process.

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