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Arch. Min. Sci. **64** (2019), 2, 297-305

Electronic version (in color) of this paper is available: http://mining.archives.pl

DOI 10.24425/ams.2019.128684

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INFLUENCE OF RHEOLOGICAL PARAMETERS OF THE FORE-SUDETIC MONOCLINE PLASTIC ROCKS ON THE PROCESS OF DRILLING BOREHOLES

WPŁYW PARAMETRÓW REOLOGICZNYCH SKAŁ PLASTYCZNYCH MONOKLINY PRZEDSUDECKIEJ NA PROCES WIERCENIA OTWORÓW WIERTNICZYCH

Plastic rocks can creep, therefore the knowledge of the rheological properties of the drilled formations is an important element of the drilling process and when choosing borehole designs. These properties of plastic formations also influence the way in which appropriate drilling technology and drilling mud properties are selected. The article presents the effect of basic rheological parameters of salt from the Fore-Sudetic Monocline deposit on the drilling of boreholes in the mining area of KGHM Polska Miedź, which in the future can be used as a good drilling practice to improve the safety and efficiency of drilling.

The process of drilling in plastic rocks may be hindered. Salt is a plastic rock and in the analyzed rock mass it is deposited at a considerable depth. The caprock exerts big loads on it, beside the temperature in the deposit intensifies the rheological properties of the rock. The creep process causes that the borehole contracts, therefore the knowledge about the rheological properties of the drilled rock is very important for establishing the safe time in which the well may remain uncased. The paper is devoted to the influence of basic rheological parameters of salt bed in the Fore-Sudetic Monocline on the process of drilling of a borehole in the area of KGHM Polska Miedź as these data can be used in drilling practice in the future.

Keywodrs: mining and engineering geology, geotechnical engineering, environmental protection in mining, drilling

Proces wiercenia otworów przechodzących przez skały plastyczne może powodować utrudnienia. Sól kamienna jest skałą plastyczną, w analizowanym górotworze zalega na znacznej głębokości, poddana jest dużemu obciążeniu wynikającemu z ciężaru nadkładu, niebagatelny jest też wpływ temperatury złoża, dzięki którym w skale spotęgowanie ujawniają się jej właściwości reologiczne. Płynięcie soli powoduje zaciskanie otworu, stąd ważnym elementem w procesie wiercenia jest znajomość własności reologicznych

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przewiercanej skały, dla ustalenia właściwej technologii wiercenia i wpływ na ustalenie bezpiecznego czasu pozostawienia otworu bez zarurowania. W artykule przedstawiono wpływ podstawowych parametrów reologicznych soli ze złoża Monokliny Przedsudeckiej na proces wiercenia otworu wiertniczego z rejonu KGHM Polska Miedź S.A, które w przyszłości mogą być wykorzystywane w praktyce wiertniczej.

Słowa kluczowe: geologia górnicza i inżynieryjna, inżynieria geotechniczna, ochrona środowiska w górnictwie, wiertnictwo

1. Introduction

The development of new, improved mining methods and technologies allows for developing and extracting copper ore resources in the mining areas owned by the KGHM Polska Miedź and deposited in the Fore-Sudetic Monocline. Among such sites is the Głogów Głęboki-Przemysłowy deposit, which may maintain the extraction of copper and the associated metals on the present level for the coming years. The recognition and research works concentrate on prospecting drilling, on the basis of which the deposits in the mining area of Radwanice-Gaworzyce, Retków-Ścinawa, Głogów, Bytom Odrzański will be documented. Attempts are also made to obtain a concession for oil and natural gas prospecting and exploration. Taking into account the technological progress, we can expect a production from documented deep copper ore deposits, which are presently classified as non-balance (after KGHM Strategy, 2017-2021).

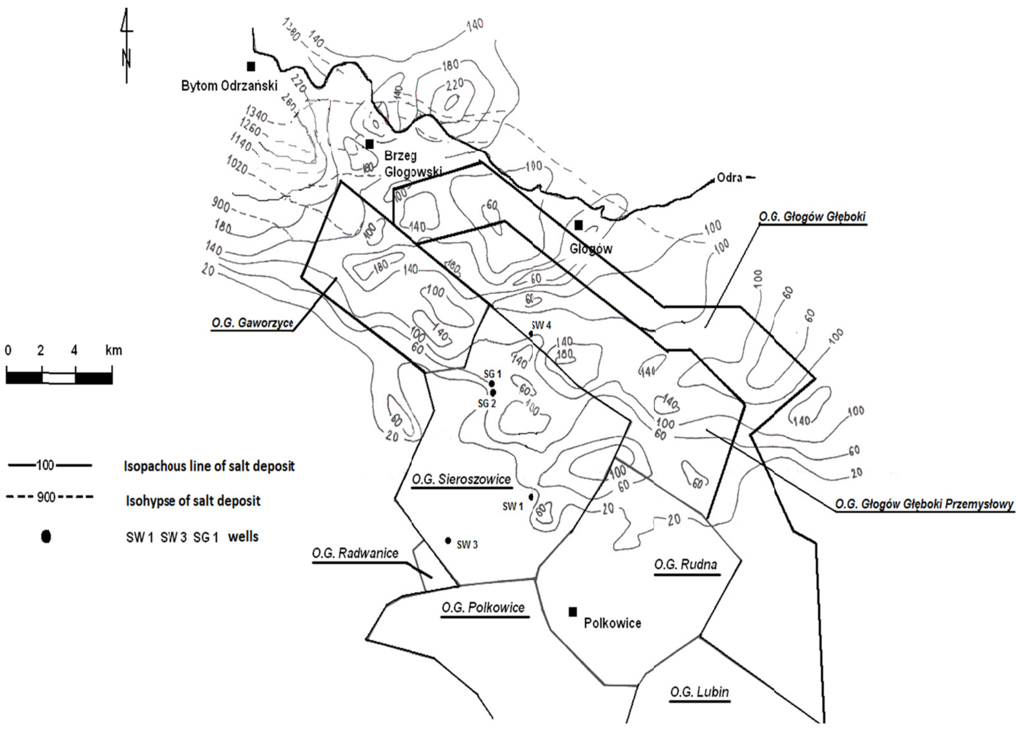

Fig. 1. Retention of salt deposits from the Fore-Sudetic Monocline against mining areas held by the KGHM Polska Miedź (after Szybist, 1994)

When considering drilling boreholes in the mining area held by the KGHM Polska Miedź in the Fore-Sudetic Monocline at a depth exceeding 1000 m b.s., attention should be paid to the possibility of reaching and drilling through a plastic layer of salt (Fig. 1) (after Szybist, 1994).

Salt rock mass at a considerable depth undergoes big stresses. This and the disturbed original state of stress reveal the rheological properties of salt. Salt has the ability to plastically creep which leads to the increasing strains of the rock mass. The wellbore gets contracted, therefore it is important to maintain the cross-section to the moment the casing is introduced and cemented, and the stress exerted by the rock mass is overtaken by it. The knowledge of rheological properties of salts coming from a definite drilling area is useful for proper wellbore designing in a given depth interval and selecting the most appropriate drilling technique and technology. Among the most important elements is the proper selection of the time of relaxation of bedded salt intervals and creep time, which directly leads to leaving the interval uncased.

2. Rheological properties of plastic rocks on the example of salt from the Fore-Sudetic Monocline

The stability of a borehole is defined as its ability to maintain the shape and location against the acting forces which tend to change this situation. When investigating and observing rock mass at great depth, attention should be paid to the time which significantly affects the state of stress and strain of the rock mass in the vicinity of workings. The time in which the rock mass is left open while the well is being drilled is not long (Kłeczek, 1994). Taking into account the specific character of plastic layers, the borehole stability is very important from the moment the drilling is over to the instance casing and cementing jobs are performed and the bonding is complete. Too fast contracting borehole may cause seizing of the tools at the stage of drilling as well as various complications or break-downs. The borehole passing through a salt bed, as in the bedded salt deposit in the Fore-Sudetic Monocline, will go through salt at a depth interval of 800-1300 m, on average 1050 m. An average thickness of the salt bed in the 85% of analyzed area totals to about 66 m (according to Szybist, 1994). The analysis of influence of rheological properties of salt on the drilling of rocks was based on data of a borehole in the Rudna Mining District. A simplified geological and geomechanical profile has been presented in table 1. The geostatic pressure exerted on the salt bed by the caprock equals to about 24 MPa.

TABLE 1

Geomechanical parameters in the geological profile of the considered test hole in the Rudna Mining District

Depth, m	Layer	γ, kN/m^3	*E*, GPa	ν
0-30	Quaternary	21.0	—	—
30-350	Tertiary	19.1	—	—
350-940	Variegated sandstone	23.2	6.6	0.25
940-1014	Anhydrite, Dolomite	26.1	10.1	0.27
1014-1076	Upper anhydrite	29.4	6.2	0.39
1076-1132	Salt	21.0	2.3	0.24
1132-1210	Lower anhydrite	29.0	6.2	0.40
1210-1250	Rotliegend	20.7	3.2	0.31

After drilling in a plastic interval (in this case salt), the initial elastic state of stress around the borehole was a result of establishing the secondary equilibrium of the rock mass. It has been assumed that casing and sealing of the columns should be performed at that stage. In a long time perspective, i.e. at the stage of stress stabilization, the structure of the rock mass may be damaged, which in the case of plastic rocks means the plastic and unlimited creep. Factors directly leading to the loss of borehole stability may be the excessive concentration of compressive stress on the wellbore walls, change of strength parameters of the rock mass, rheological processes acting on casing with incorrectly selected strength, or erroneously performed cementing jobs. All these factors may lead to a break-down.

Modeling of convergence of the working in laboratory conditions is based on the creep tests performed on creep testing machines (Kłeczek & Filcek, 1969). The laboratory samples were exposed to stress corresponding to the pressure at a given depth. The deformation of the sample in time was measured when the conditions stabilized. The character of behavior of rocks in given conditions, and the mechanism responsible for their damaging could be identified based on the observation of this effect. Underground objects in a definite geological location can be correctly designed on the basis of known rheological rock material constants and the analysis of state of stress and strain.

The creep effect takes place in three stages: primary creep associated with rock strengthening (creep rate $d\varepsilon/dt$ decreases), steady creep ($d\varepsilon/dt$ is constant) and final creep ($d\varepsilon/dt$ increases) (Fig. 2). If a constant load on a sample is exerted for a sufficiently long time, the creep process leads to the de-cohesion and damaging of the sample in time which is needed to destroy the rock t_{kr}.

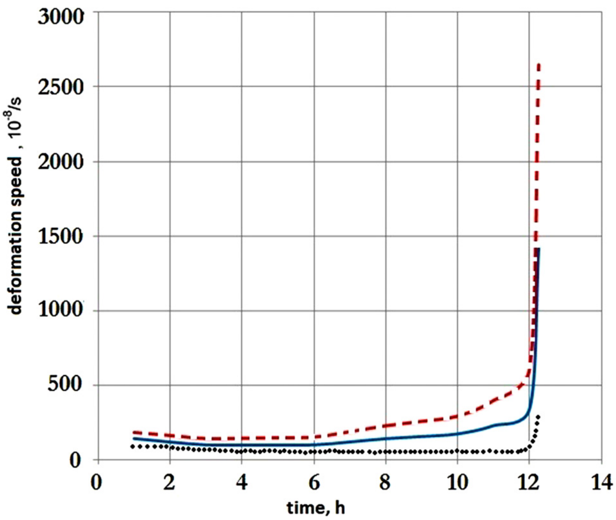

Fig. 2. Graphs of longitudinal creep velocity (dotted line), transverse (solid line) and volume (broken line) representing a depenence of the tested sample on time

Rheological properties of the rock mass and prediction of behavior of the rock mass in a time corresponding to its proper useful function is based on the classic object-design condition, in that boreholes, as the admissible stress values are not exceeded (1)

$$\sigma \le \sigma_{dop} < \sigma_{kr} \tag{1}$$

(σ_{dop} – admissible stress, σ_{kr} – critical stress at which the construction is damaged). In the case of rocks having rheological properties, this design condition should account for an assumption that the time of some drilling operations should be limited, not to exceed the time needed to destroy it (2)

$$t < t_{kr} \tag{2}$$

and limit the deformations in the vicinity of the borehole when drilling jobs are performed, which cannot exceed the maximal admissible deformation

$$u(t < t_{kr}) < u_{\text{maks}} \tag{3}$$

(u_{maks} – biggest admissible deformation) (Chrzanowski, 1995).

Based on the measured linear absolute longitudinal (λ_z, mm/mm) and diameter (λ_d) strains, the following unit strains of a sample are determined: longitudinal (ε_z), transverse (ε_d) (4) and volume (ε_v) (5) with the formula

$$\varepsilon_z = \frac{\lambda_z}{h}; \ \varepsilon_d = \frac{\lambda_d}{d} \tag{4}$$

and

$$\varepsilon_V = 1 - (1 - \varepsilon_d)^2 (1 - \varepsilon_z) \tag{5}$$

(h – height of sample, d – diameter of sample).

The stage of the unsteady creep was very short. After 2 hours the maximal creep rate in the vertical and horizontal directions assumed constant values and the process continued for about 10 hrs. The last 2 hours of the creep test were a progressive creep which ended in damaging of the sample. It should be noted that the transverse strains increased at the stage of steady creep twice as fast as its longitudinal equivalent (Fig. 2). In the process of deformation of the analyzed samples at a constant compression load, an absolute increase of their volume was observed. Strong dilatation was observed when the creep effect appeared due to the microfracturing of the rock material, starting from the stage when a specific load was applied (Kwaśniewski, 1986).

The creep curve $\varepsilon = f(t)$ obtained in the course of the analyses was approximated with the Maxwell's rheological model (Kłeczek, 1994) (Fig. 3), the fit of the curve and selected rheological model was high (0.98) thanks to which the rheological constants for rocks could be determined.

Having assumed that rock mass is an elastoplastic medium, and using the equation of state for Maxwell's rheological model (6), (Kłeczek, 1994).

$$\sigma = \lambda \frac{d\varepsilon}{\text{dt}} - \tau \frac{d\sigma}{\text{dt}} \tag{6}$$

there were established rheological parameters of the analyzed salt and the coefficient of linear viscosity $\lambda = 4.29 \cdot 10^{13}$ [Pa·s]. Knowing the properties of elastic salts defined in the pre-dilatation interval of stresses (Kłeczek & Zeljaś, 2012), the time of stress relaxation (7)

$$\tau = \frac{\lambda}{G} \tag{7}$$

was defined, where G was the Bulk Modulus coefficient equal to 0.939 GPa and τ = 11.2 hrs.

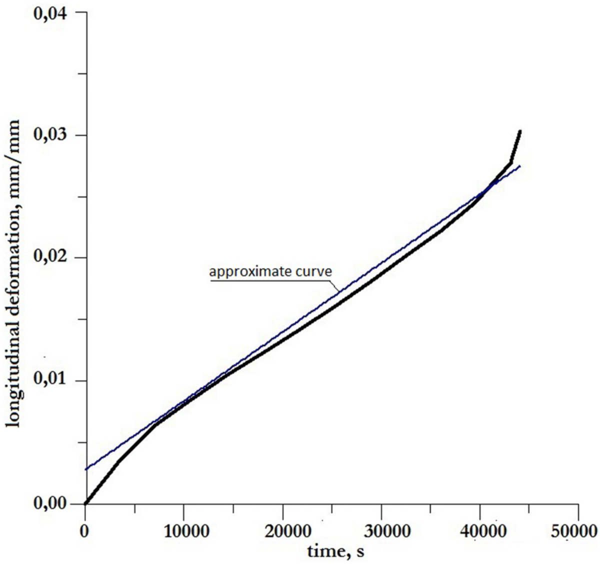

Fig. 3. Approximation of the experimental creep curve using Maxwell's rheological model

3. Design and technology of drilling boreholes in the area of copper ore mines owned by the KGHM Polska Miedź

Presently the drilling activity on the area of the KGHM Polska Miedź concentrates on the exploration drilling. The number of boreholes drilled for recognition and useful purposes still increases. By the end of the 20th century the area was recognized with almost 500 boreholes of the total footage of 440 000 m. In the successive years the drilling network was densified. Presently, the works strongly focus on drilling new boreholes for 'ice water' which will be used for air conditioning in the mining workings.

In the last years over 120 boreholes were drilled to provide additional information about the mining and geological conditions. These were boreholes drilled from the surface, 1/3 of them with coring.

Drilling salt beds and other strata prone to plastify under the influence of the caprock and temperature (and consequently creep), affects the borehole construction. As far as drilling is concerned, such beds lead to complications or even drilling failures. The change of the borehole diameter due to the convergence of unstable layers may result in seizing of the drill string, casing or increase the cost of the borehole because of the periodic workovers and hoisting operations. The necessity to workover plastic intervals is connected with additional hoist jobs, faster wearing of drilling tools, loss of nominal diameter when reaming the borehole. These factors elongate the drilling jobs, and so their cost.

The design of boreholes drilled from the surface in the area under concessions for prospecting and exploitation held by the KGHM Polska Miedź is typical of the Fore-Sudetic Monocline. Based on the drilling experience gained over years in that area, a standard design could be worked out. The difference in the boreholes design stems from the depth of deposition in various areas, as well as the purpose and depth of drilling. The differences are also connected with the final diameter of the boreholes, number of applied casing and depth of their seating. The unification mainly concerns the design of the borehole as far as the surface casing and conductor casing are concerned.

The depth of the borehole depends on the area in which drilling is performed, and the depth of deposition of ore intervals. In view of the recognition and development of deposits in the northwestern part of the cupriferous area, the boreholes have been drilled even to a depth of H_o = 1500 m, about 1250 m on average. The borehole diameter is mainly predetermined by the purpose of drilling. In this case attention should be paid to typical test boreholes (recognition of the geological build of the deposit, evaluation of resources, hydrogeological tests) and useful boreholes (exploitation, piezometers, technical). The aim of drilling also determins the number of drilling columns tripped to the borehole.

A typical borehole in the northwestern part of the cupriferous deposit consists of three or four casing columns. The surface column insulates the weakly compact, near surface Quaternary layers and is driven to their bottom or top of the Tertiary. On average, the casing shoe is deposited at about 40 m of depth. Then the conductor casing is tripped most frequently to the top of the Triassic, where compact rocks occur. The average depth for the conductor casing is 400÷440 m. The depth of another casing column depends on the designation of the borehole. In the case of useful boreholes (e.g. doublets with recovery and injection of ice water, piezometers) the intermediate column is lowered to a depth of about 700 m. The shoe is also set in the Triassic, or to be more specific, in lower variegated sandstone. The placing of another column depends on the final depth of the borehole. In the northwestern part of the concession area owned by the KGHM Polska Miedź the respective depths are of 1250÷1500 m. In the case of typical exploration boreholes, which are closed after their mission is complete, are cased with two or, more rarely, with three casing columns.

The diameters of casing columns in the case of exploration-test boreholes, which are usually cored with a classic coring apparatus or with a core barrel, depend on the number of columns; these are: surface column – 13 3/8”, conductor column 9 5/8” and possibly intermediate column or production column 7” after the borehole was transformed into, e.g. a piezometer. In the case of useful drilling boreholes (e.g. for ice water recovery) with production column, the following diameters of the columns are used: surface column 30”, conductor column 24 1/2”, intermediate column 18 5/8” and production column13 3/8”.

4. Influence of rheological parameters of salt rock on the drilling of boreholes

The salt bed in the concession area of the KGHM Polska Miedź is mostly deposited at a depth of 860÷1100 m and mainly occupies the mining area of the Polkowice-Sieroszowice mine and Rudna mine (in the northern part). The thickness of the bed in the mining area is 10÷100 m or more, whereas the average thickness in the Rudna Mining District is about 50 m.

When typical borehole designs were applied, salt beds in the Fore-Sudetic Monocline in the mining areas belonging to KGHM Polska Miedź were at the final stage of drilling. In the case of useful boreholes drilled to a depth of 1200÷1500 m, salt beds were drilled in about half of the interval between the shoe of the intermediate column and the final depth. Drilling of the test boreholes is less dangerous as far as the properties of plastic salt are concerned. In the course of coring, a classic borehole is transformed when the coring apparatus is being tripped and drawn out, besides no casing column has to be introduced in the salt interval.

Performing useful boreholes is connected with the need to trip exploitation columns or intermediate columns. When doing so they can be seized at the stage of tripping in or clenched after they are already in the borehole.

The time of drilling a borehole can be divided into: productive (operation of the drilling tool, tripping and drawing out of the string set, replacement of the tool, adding part of the string, reaming, washing, workover, replacement of the string and cables, technological measurements, casing and cementing, auxiliary jobs technological idle time) and non-productive (drilling breakdowns, machine failures, complications, preventive maintenance and unplanned idle time). Accordingly, the time in which the unstable and plastic layers are exposed in the uncased borehole depends on the total time of work of the drilling tool downhole plus additional drilling operations till the moment cement is injected (cementing casing columns) and hardened (Gonet at al., 2018; Lubaś & Rado, 2004).

The analysis of the time of drilling of an interval containing salt, and also times of particular drilling operations needed to drill and case the borehole reveals that potential hazard in the borehole caused be the change of inner diameter can be indicated and assessed. As already mentioned, the time of relaxation for salt beds (τ) in the area of the Rudna Mining District (for stresses at the depth of their deposition) was on a level of 11.2 hrs. The time of drilling boreholes differs and depends on their design and final depth. Another factor is the assumed drilling technique, e.g. a smaller diameter borehole is drilled, then it is reamed when the applied rig has insufficient technical parameters. Analyzing exemplary boreholes drilled in a geological profile (as in table 1) to a depth 1200÷1250 m, cased with four columns, as for a useful borehole, it can be assumed that the average time (t_{wo}) of performing such a borehole (without mounting and dismounting of the rig) is 3384 hrs. The average time of drilling an interval for a casing column in boreholes with plastic salt layers equals to 984 hrs with a standard deviation of 284.7 hrs. The average time of performing drilling jobs (t_{rw}) in these boreholes totals to 754.5 hrs (at σ_{rw} = 284.7 hrs). The average technical rate of penetration (V_t) for such boreholes equals to 0.626 m/h, (at σ_{Vt} = 0.16 m/h), whereas the average velocity of the drilling cycle (V_m) is on the level of 0.738 m/h (at σ_{vm} = 0.14 hrs). The mechanical velocity (V) in the analyzed boreholes was 14÷18 m/h.

5. Conclusions

1) In the northwestern area of the KGHM Polska Miedź, plastic salt layers are deposited in about half of the stripped out interval, where the drilling is planned. Depending on the end depth of the borehole, after drilling the salt layer, there still remains about 200÷300 m to go to reach the planned depth of the borehole.
2) Taking into account the average indices of drilling for the analyzed boreholes, e.g. average velocity of drilling cycle, the drilling of such intervals will take about 270÷400 hrs. Drilling at greater depths is connected with lower advancements, which increases the time of drilling of the interval.
3) The analysis of the obtained values of time needed to drill intervals with plastic salt layers in the Fore-Sudetic Monocline reveals that the borehole stability in the course of

drilling will be disturbed. The creep rate of the salt layer is much faster than the time needed for drilling intervals below the plastic beds.

4) Having assumed that the borehole is drilled uninterruptedly with the average mechanical rate of penetration of 15 m/h, the time needed for drilling a borehole in the interval of 200÷300 m would be about 13÷20 hrs, depending on the depth, which exceeds the creep time. If the removal of the drill string is followed by pre-casing and cementing jobs, the time in which the uncased part of the borehole is exposed is considerably elongated. For this reason the creep time of salt layers should be taken into account when planning the borehole design and particular jobs in the borehole.

Creating salt creep models for drilling areas helps one determine the admissible time of exposition of uncased borehole intervals, as this is important for the planned design and then safety of performance.

Acknowledgement

Paper performed within subvention at the Department of Drilling and Geoengineering FDOG AGH-UST in Kraków no 16.16.190.779

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