www.czasopisma.pan.pl www.journals.pan.pl

Arch. Min. Sci., Vol. 58 (2013), No 3, p. 629–642

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

DOI 10.2478/amsc-2013-0044

TADEUSZ MAJCHERCZYK*, ZBIGNIEW NIEDBALSKI*, DANIEL WAŁACH*

VARIATIONS IN MECHANICAL PARAMETERS OF ROCK MASS AFFECTING SHAFT LINING

ZMIANY PARAMETRÓW MECHANICZNYCH GÓROTWORU I ICH WPŁYW NA OBUDOWĘ SZYBOWĄ

The paper presents geomechanical properties of rock mass occurring in the initial section of shaft lining during its execution. The shaft being sunk is surrounded with cohesive soils, mainly clays with sand layers and silts. Such lithology causes that in various levels some parts of strata are saturated with water. This results in a considerable changeability of soil properties in time. With high water content, the soil is washed away leading to local loss of contact between shaft lining and surrounding soils. This, in turn, results in lack of proper support for curbs and shaft lining fracture in some sections. Engineering activity in such a case should embrace sealing injections in selected parts of the shaft in order to resume proper reinforcement in the lining-rock mass system. The studies of the soils surrounding shaft lining were supposed to help design curbs with increased bearing capacity. The tests of soils indicated that the angle of internal friction and cohesion do change not only at different depths but also at the same depth in different points of perimeter. It was also observed during the study that the mechanical parameters of the analyzed soils improve as the distance from the shaft lining increases, which clearly indicates change of soil properties in the direct neighborhood of the shaft. Considerable number of tests carried out in the study allowed to determine the relationship between water content and angle of internal friction or soil cohesion. The determined relationships can help to estimate change of soil properties under the influence of water with considerable precision. The reinforcement of curbs executed with the use of ground anchors allowed for further shaft sinking. The tests of concrete used in the shaft carried out in the analyzed section produced results similar to the values assumed in the project.

Keywords: mining, shafts, properties of soils, shaft lining

W artykule przedstawiono charakterystykę własności geomechanicznych górotworu jakie występują podczas drążenia szybu w jego początkowej długości. W otoczeniu głębionego szybu występują grunty spoiste, głównie w postaci glin z przerostami piasków oraz pyły. Taka litologia powoduje, że na różnych poziomach część warstw gruntu jest zawodniona. Wpływa to na dużą zmienność własności gruntów wokół szybu oraz zmiany tych własności w czasie. Przy dużym zawodnieniu grunt był wymywany zza obudowy, co prowadziło do lokalnej utraty kontaktu pomiędzy obudową a otaczającym gruntem oraz braku właści-

* AGH UNIVERSITY OF SCIENCE AND TECHNOLOGY, AL. A. MICKIEWICZA 30, 30-059 KRAKOW, POLAND

wego podparcia dla stóp szybowych. Efektem tego było na niewielkim odcinku szybu pękanie obudowy. Podjęte działania, które sprowadziły się do wykonania iniekcji na pewnym odcinku szybu doprowadziły do przywrócenia właściwej współpracy obudowa – górotwór. Przeprowadzone badania gruntu zza obudowy posłużyły do podjęcia działań w celu zwiększenia nośności stóp szybowych. Badania gruntu wykazały, że kąt tarcia wewnętrznego oraz spójność zmieniają się nie tylko na poszczególnych głębokościach, ale także obserwuje się duże różnice dla próbek pobranych z tej samej głębokości ale z różnych punktów na obwodzie szybu. Badania wykazały także wzrost parametrów mechanicznych badanych gruntów wraz z oddalaniem się od obudowy, co świadczy o zmianie własności gruntów bezpośrednio w sąsiedztwie szybu. Duża liczba wykonanych badań pozwoliła na opracowanie zależności pomiędzy wilgotnością a kątem tarcia wewnętrznego i spójnością. Na podstawie uzyskanych zależności można szacować z dużą dokładnością zmianę własności gruntów pod wpływem działania wody. Zrealizowane wzmocnienia stóp szybowych z wykorzystaniem kotew gruntowych pozwoliły na podjęcie dalszego głębienia szybu. Przeprowadzone na analizowanym odcinku badania betonu z obudowy szybu wykazały wartości zgodne z projektem.

Słowa kluczowe: górnictwo, szyby, parametry górotworu, obudowa

1. Introduction

Shafts are the most important excavations in underground mining due to their central role in the whole mining process. In almost all Polish underground mines, shafts are the only way to access the deposit during its exploitation and they also serve the purpose of transporting personnel and material. Shafts additionally provide access for ventilation. In most cases coal mines in Poland possess at least several shafts since driving underground headings is rarely used for deposit completion. Due to high driving costs and long duration of their existence, as well as the necessity of assuring high safety levels, the shaft sinking process is carefully controlled.

In Poland, shaft sinking in variable geological conditions has very long traditions. Between 1945 and 1989, over 260 km of shafts were driven, mostly in hard coal and copper ore mining (Wichur, 2007). Furthermore, a great number of shafts were deepened as mining had to be moved to lower drawing levels. As a result of the restructuring of the hard coal mining in Poland, a number of shafts underwent liquidation process. However, the fact remains that despite successive investments, the need exists to introduce untypical technical solutions to overcome the still greater challenges faced. In the case of shaft driving from the surface, problems related to the occurrence of thick overburden composed of clays with low strength parameters and loose soils saturated with water constitute the greatest hazard to shaft stability. In the case of shafts driven through rock, the difficulties result from such factors as the occurrence of salt beds, excessive depth, tectonic deformations, local rock mass weakening, water content, influence of former exploitations and seismic activity (Sadaghiani & Bieniawski, 1990; Bruneau et al., 2003; Ortlepp et al., 2008).

The basic method applied in sinking shafts in cohesive soils is mechanical mining, whereas in hard rocks – mining with the use of explosive materials (Hartman, 1992). In the case of weak rocks or the ones saturated with water, shaft sinking is executed after freezing the rock mass (Vergne, 2003; Wichur, 2007).

In hard rocks it is possible to build the shaft without any lining (Pariseau, 2007), nevertheless this solution is not practiced in Polish mining conditions, hence all shafts are reinforced with lining as a rule. Shaft lining should be designed according to the Polish norm PN-G-05015 (1997), however in complex cases computations can be complemented with other analytical methods (Bulychev 2008, Wichur 2005). According to the norm regulations, shaft lining can be built with bricks, bentonite, concrete, reinforced concrete, tubbing and reinforced concrete panels.

Hydroisolation can be made with the use of polyvinyl chloride (PVC) films, polyethylene (PE) films, tightly connected reinforced concrete or steel panels and sprayed chemical substances. In order to protect underground headings or during geotechnical works aimed at slope, embankment or trench stability reinforcement, bolts are commonly used (Wyllie & Mah, 2004; Majcherczyk et al., 2012). So far in Polish mining conditions, no anchoring solutions have been practically applied, which results from lack of entries related to bolting technology applications in the official Polish norm PN-G-05015 (1997).

The paper presents the study of geotechnical parameters of soils occurring during shaft sinking and their influence on the selection of proper parameters for shaft lining. Mining, geological and technical conditions were analyzed in relation to changing properties of rock mass surrounding the shaft and the need to increase shaft lining bearing capacity. The planned upgrade of shaft stability was based on two crucial elements: (1) reinforcement of shaft lining and (2) increasing strength parameters of rock mass. A particular hazard stemmed from non-uniform loading of executed shaft lining, which could lead to the occurrence of shearing or tension stresses in the lining construction. The paper also presents the results of rock mass tests obtained during shaft sinking, as well as some recommendations pertaining to the application of innovative technological solutions in rock mass and shaft lining construction reinforcement.

2. Geological conditions and shaft parameters

The analyzed shaft is located in the southern part of Upper Silesian Coal Basin and in 2013 it was deepened. The geological profile indicates that in the section from the surface down to 24.0 m there appear Quaternary formations of silty clay, silty sands and medium-grained sands. Deeper, down to 738.5 m, Tertiary formations are deposited, mainly cohesive clay. In the ultimate section of Tertiary formations, i.e. at 577.0÷738.5 m, marly claystones with fine-grained sandstone occur. Carbon layers deposited below the level of 738.5 m mainly consist of shale and sandy shale with sandstone inclusions and coal layers.

Due to functional reasons, the shaft was designed as a descending and service shaft. It is also a downcast shaft as far as its ventilating function is concerned. The basic technical parameters of the shaft pertaining to its designed functionality are as follows: shaft diameter with final lining is 8.0 m and shaft depth is approx. 1,200 m.

At the distance of 30 m below terrain surface, the lining was designed as a monolithic concrete lining with the thickness of 0.8 m. In further section it was designed as a combined lining with concrete (internal column) and prefabricated elements/panels (external column). The internal column made of concrete class C30/37 was planned for the thickness of either 0.55 m or 0.75 m depending on the expected bearing capacity. The external column made of prefabricated elements was planned for the thickness of 0.20 m with the concrete class C30/37. The radius of the applied panels was either 4.55 m or 4.75 m, whereas the height was 0.75 m. Empty space between rock mass and panels was filled with concrete creating leveling layer with the thickness of minimum 0.10 m.

During shaft sinking, it was indicated that in the vertical profile there appear condensed silty clay and condensed clay with silt layers saturated with water, fine and silty sand, as well as fine-grained, marly and very weak sandstone. The formations in the analyzed section generally have condensed to hard-plastic consistency, locally plastic, and they are not resistant to water, i.e. rock mass soaks and swells in a medium with high water content.

During hydrogeological studies carried out in the deepened shaft at the depth of 78÷156 m scattered water leakages from shaft walls were observed, whose volume reached approx. 5 l/min. However, starting from the depth of approx. 235 m to approx. 300 m, leakage of water into the shaft increased dramatically, reaching as much as 130 m^3/min. The existing water-bearing horizons and washing out soils from behind the lining caused such damage to shaft lining as horizontal and vertical fracture. Repair actions were divided into three phases. In the first phase, the caverns behind the lining were filled. The second phase embraced testing soil parameters, which were used in the third phase in order to reinforced shaft lining.

3. Study and repair action description

3.1. Phase I – filling of caverns behind the lining

The damage that occurred in the shaft called for the implementation of reinforcement measures. In order to achieve this purpose, injections of mineral cement and polyurethane were made in the damaged section of the shaft, i.e. at the length of approx. 80 m. For the sake of injections approx. 1,400 holes were drilled at 64 levels, with the total length of almost 3,500 m. The number of holes at a given level usually ranged between 16 and 25 (Fig. 1). The holes were drilled horizontally or with a slight downward deviation from the horizon. The length of holes was also variable and ranged between 1.1 to 4.75 m.

The distribution of injection agent use in the reinforced section of the shaft was not regular. The smallest volume, i.e. approx. 10% of the total, was used at the depth 205÷235 m, whereas the largest volume was used in the section 265÷285 m of the analyzed shaft fragment (Fig. 2). Furthermore, the varied volumes of injected agent were observed depending on the direction, which suggests irregular distribution of caverns behind the shaft lining at the same level (Figs. 3 and 4).

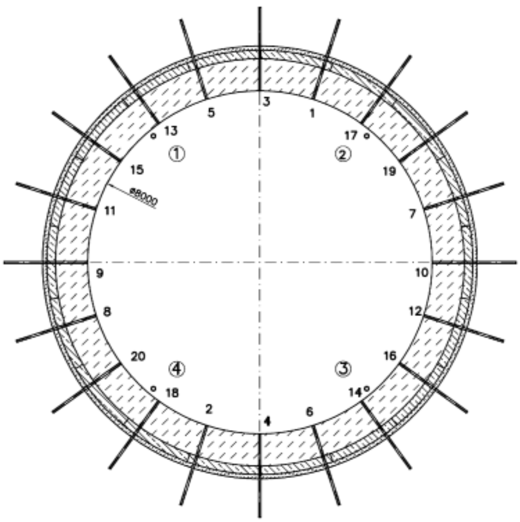

Fig. 1. Scheme of injection holes distribution in shaft perimeter at the depth 209 m

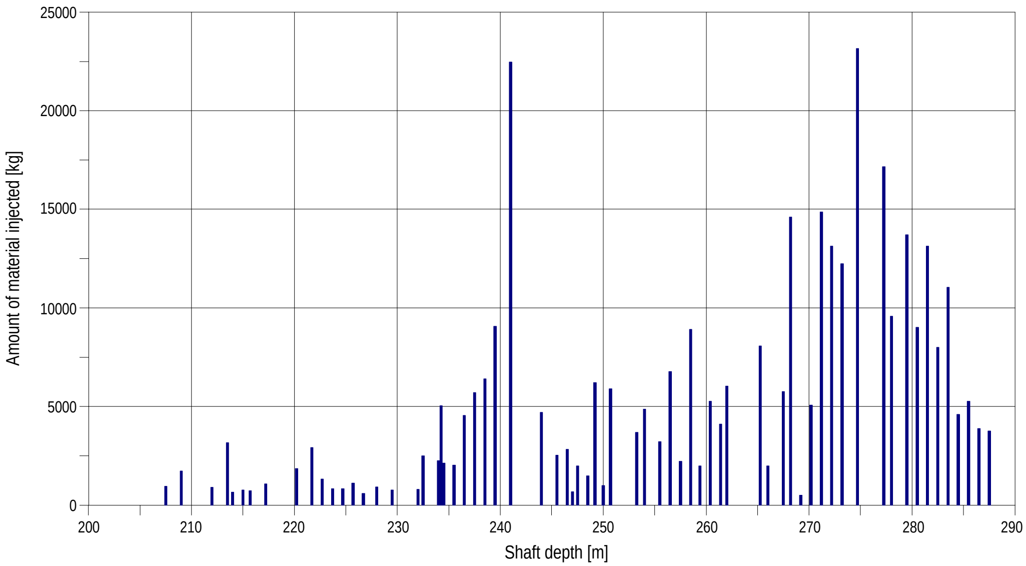

Fig. 2. Volume of agent injected behind shaft lining depending on depth

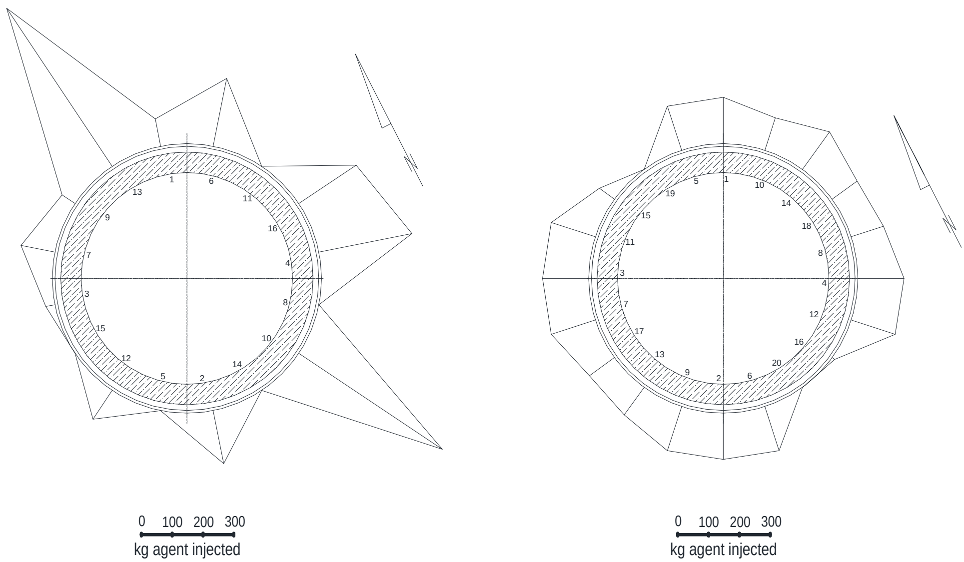

Fig. 3. Volume of agent injected in particular holes at levels 232.5 m and 234 m

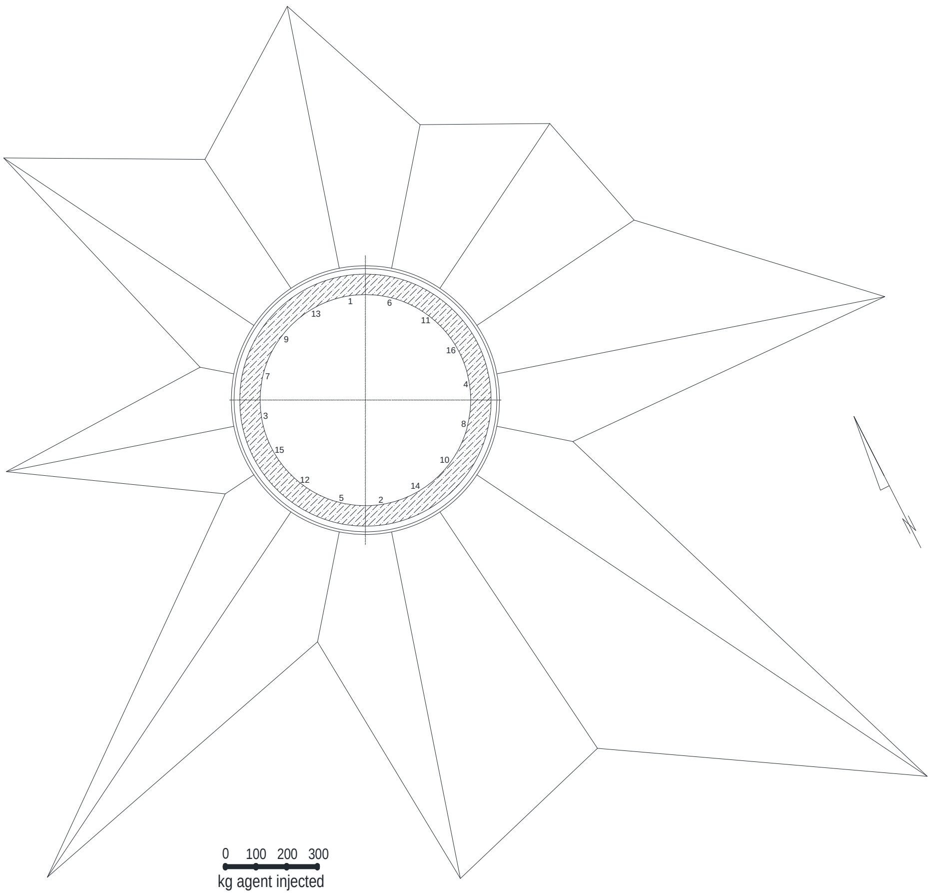

Fig. 4. Volume of agent injected in particular holes at level 273.2 m

3.2. Soil property evaluation

In order to evaluate soil properties for designing system of shaft lining reinforcement, a series of tests were carried out including boring core holes at shaft levels 211.0 m, 221.0 m, 233.5 m, 244.5 m, 255.0 m, 265.6 and 278.5 m. The holes, in which mainly clay and silt occurred, were drilled in four directions: northbound, southbound, eastbound and westbound. Length of particular holes alongside with lining thickness reached approx. 5.0 m. As part of the research, the following parameters were determined: cohesion, internal friction angle, water content and, additionally, compressive strength. The study indicated that even at the same level of sample collection, in different directions of the shaft the obtained results vary significantly (Figs. 5÷8).

In the case of cohesion, the most significant changes of values at the same depth were observed in the level 211 m, where – depending on the direction of a particular hole – cohesion varied from 400 kPa for samples taken from western direction to 980 kPa for samples collected from eastern direction (Fig. 5). Almost a two-times differences in values were recorded also at the levels of 233 m and 244.5 m, however cohesion varied in the range from 250÷280 kPa to 530÷590 kPa. In the majority of cases cohesion value ranged between 400 and 600 kPa.

Slightly less significant variations were observed for the values of internal friction angle, nonetheless they are still noticeable in this instance (Fig. 6). As in the case of cohesion, the largest variations were observed in the levels 211.0 m, 233.0 m and 244.5 m. Minimum value angle of internal friction in this case was 11° (level 244.5 m – East), whereas the maximum was 28.5° (level 211.0 m – also East).

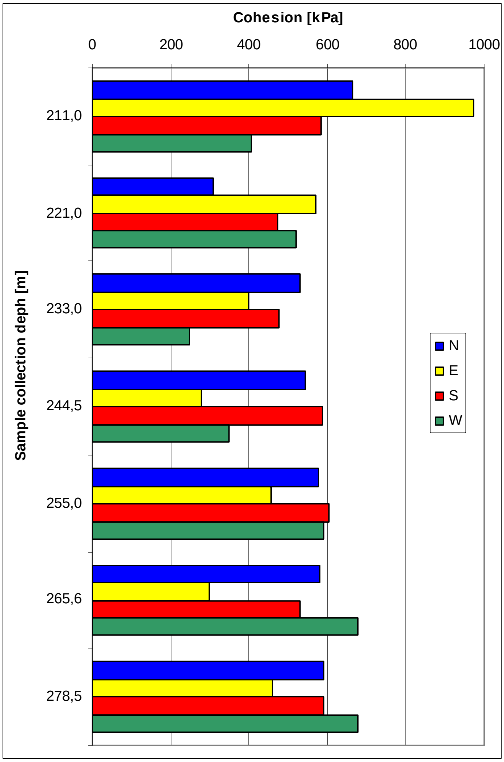

Fig. 5. Cohesion change in particular levels

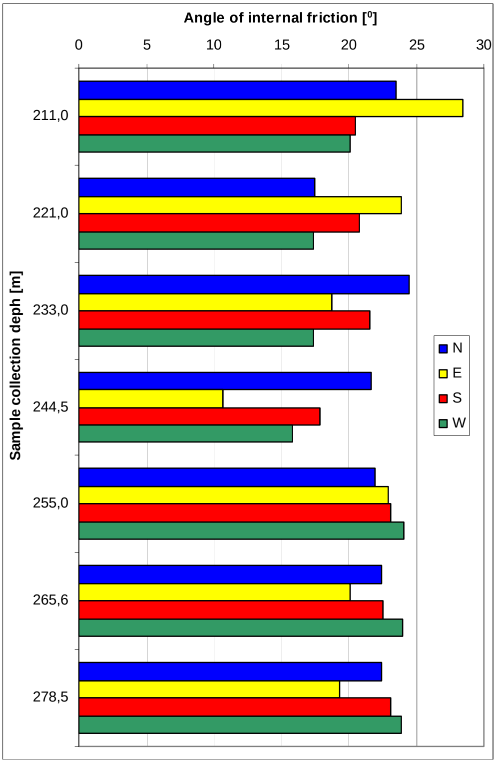

Fig. 6. Change angle of internal friction in particular levels

Also water content was determined since it is an important parameter affecting mechanical properties of soils. It should be pointed out here that water content of the samples was approximate to natural as after drilling the cores, the samples were hermetically packed and the tests were made in the shortest time possible.

As it can be clearly observed in Fig. 7, the differences in obtained values of water content occurred not only in different levels but even in the holes drilled in one level. The lowest values of water content ranging between 9 and 13% were recorded in the levels 211.0 m, 265.6 m and 278.5 m, whereas the highest values, i.e. approx. 12÷17%, were observed in the levels 233.0 m, 244.5 m and 255.0 m.

In the case of obtaining material in a very cohesive form, cubic and cubicoidal samples were prepared, which were subject to testing their compressive strength (Fig. 8). Variation of this parameter is highest among all other analyzed ones, as it ranged from only 1.1 MPa in the level 244.5 m (West) to as much as 9.8 MPa in the level 211.0 m (East).

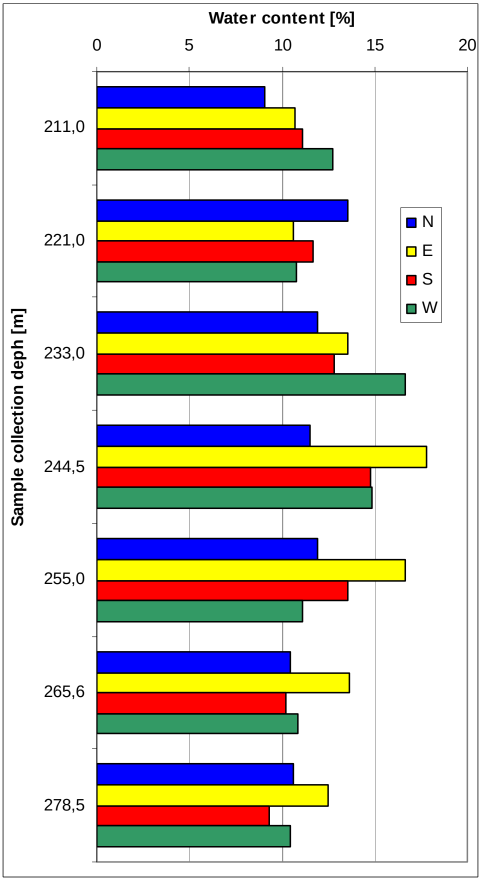

Fig. 7. Change of water content in particular levels

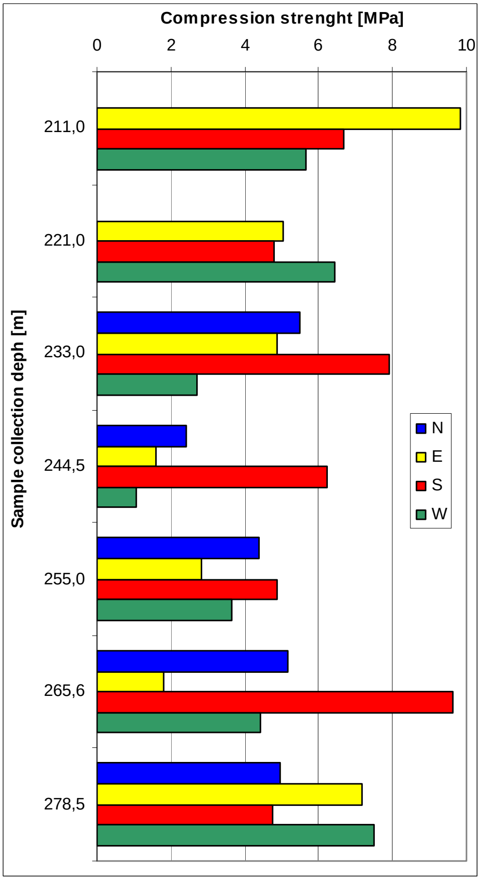

Fig. 8. Change of compression strength in particular levels

Testing properties of clay with sand inclusions and marly silt taken from behind the shaft lining indicated significant variations in analyzed parameters. Changes angle of internal friction in relation to the distance from the lining in selected study levels clearly indicate that the values grow as the distance from the lining contour increases (Fig. 9). Also increase of sample collection depth resulted in the growth of average values of internal friction angle. The study also proved a significant influence of water content on mechanical parameters of the rock mass. As the diagram shows, the water content of the analyzed clay with sand inclusions varied in the range 8÷30%, whereas the internal friction angle determined in the tests of direct shearing ranged between 5 and 42° (Fig. 10). The relationship between these parameters is clear and the coefficient of determination for the exponential equation is R^2 = 0.604. Also cohesion for clay depends on water content, however the correlation of results appears in approx. 50% cases as the coefficient of determination is R^2 = 0.51 (Fig. 11).

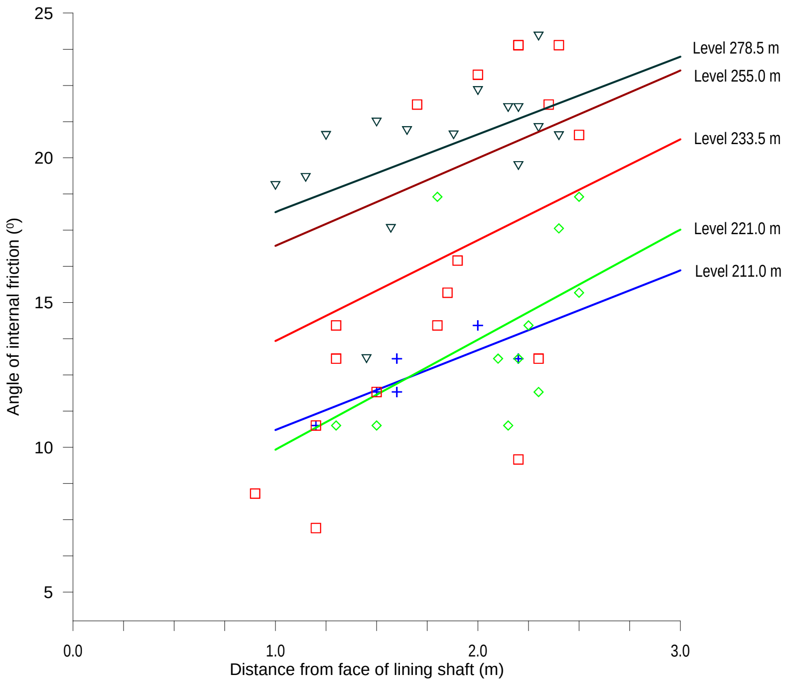

Fig. 9. Values angle of internal friction in particular levels

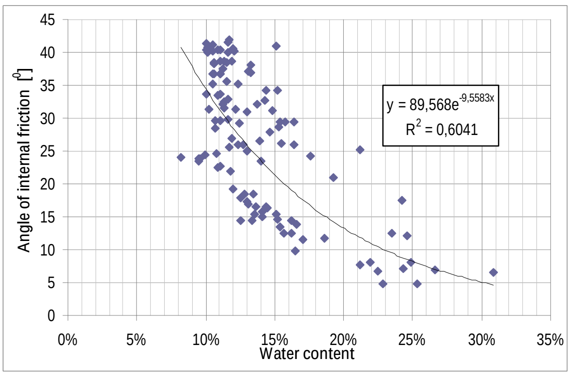

Fig. 10. Relationship between angle of internal friction and water content for clay with sand inclusions

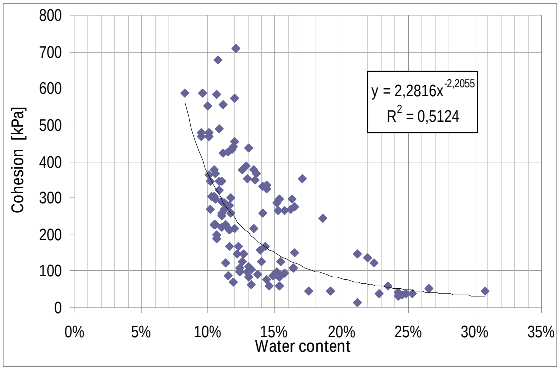

Fig. 11. Relationship between cohesion and water content for clay with sand inclusions

In the case of silt layers subject to similar analyses, it was concluded that the relationship between internal friction angle and water content is even larger, as the coefficient of determination is $R^2 = 0.78$ (Fig. 12). A much lower correlation was obtained between cohesion and water content of silt – for the assumed logarithmic equation, it was only 21% (Fig. 13).

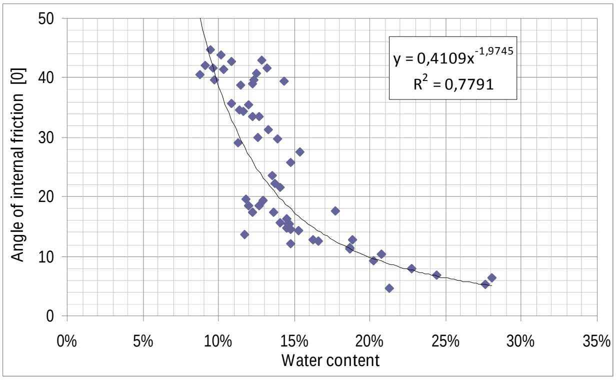

Fig. 12. Relationship between internal friction angle and water content for marly silt

During the study, the relationship between mechanical parameters and water content were determined for a particular material of the rock mass. Samples obtained in further distances from the shaft lining or from below the bottom contour of the shaft usually had lower water content than the saturation recorded directly near the shaft lining or in its bottom. The diagrams below allow estimating mechanical parameters on the basis of water content. Carrying out further studies can help to enlarge the database and fit the function correlations better.

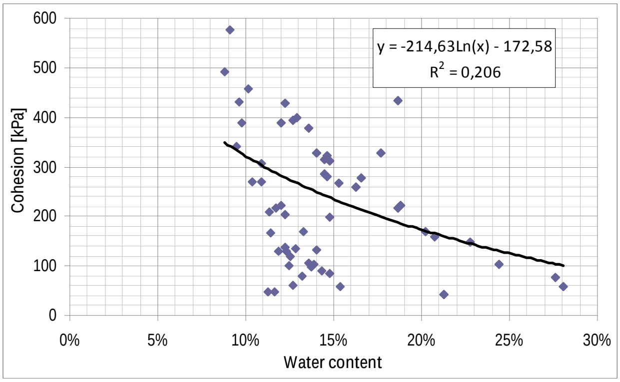

Fig. 13. Relationship between cohesion and water content for marly silt

3.3. Shaft lining reinforcement

The determined parameters of soil outside the lining helped to design shaft lining reinforcement. In order to increase the bearing capacity of the lining, anchoring in four levels in the place of curbs was applied. The bolts were installed at the angle of 45° upwards in relation to the shaft's axis. Such angle selection was assumed as a compromise between maximal utilization of the vertical component of bolts' bearing capacity and a possible removal from the unstressed zone resulting from the shaft influence. It was assumed that the carrying rock mass begins approx. 3.5 m behind the shaft breakout. A 6-meter section of bars not connected with the rock mass or with the shaft lining was used for providing the initial tension for the bolt (Fig. 14). Due to the lack of tension capacity of the concrete ring, a special steel construction in the form of a ring was designed, taking over tensile loading from the bolts. The ring was installed in a special groove made in the existing lining, with the height of 0.6 m and minimum depth of 0.25 m.

In order to reinforce the curbs, injection bolts with the bearing capacity of 260 kN were used. The bolt rod consists of a steel bar in the form of a pipe with the external diameter of 51 mm and

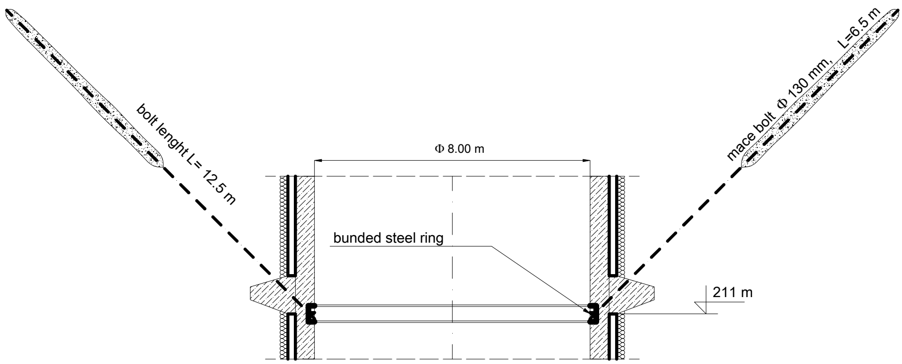

Fig. 14. Scheme of the shaft reinforcing with bolts

internal diameter of 34.5 mm, threaded on all its length, as well as connectors. Both the bars and the connectors are made of steel with plasticity limit of 580 N/mm^2.

All bolts have a free section (active zone) with the length of 6 m and a bolt mace. The mace of each bolt is made within just one rock layer. The loading capacity of lateral surface of the mace was determined assuming average parameters of soil obtained during control tests behind the shaft lining. The mace, which transmits loading from shaft arming to the rock mass, is made of Portland cement with the minimum strength of 35 MPa. After installing particular bolts – nonetheless not earlier than after a fortnight – each bolt was compressed with the force of 160 kN (i.e. approx. 60% of calculated loading capacity).

3.4. Evaluation of shaft lining condition after reinforcement

In order to evaluate the condition of shaft lining after reinforcement, strength parameters of the lining were checked by means of non-destructive tests using ultrasonic defectoscopy directly in the shaft.

As the access to the construction was limited only to one side, the study was carried out according to the methodology recommended by RILEM (The International Union of Laboratories and Experts in Construction Materials, Systems and Structures). As the observations of phenomena related to surface damage (corrosion, frost damage) requires at least several records in the bases of varied length, two-point recording heads with switchable receivers and possibility to change distance between them in the range 200,350 mm were used.

Wave velocity is related to strength of a given medium, nonetheless the relationship is of empirical character. It can be described with first-degree or second-degree polynomials offering sufficient precision for practical purposes. Time measurement and velocities of various forms of waves determined on this basis are absolute parameters describing strength and deformation properties of the medium. The measurement is based on the rule of a multi-point receiver. In this method, time readings are taken by means of moving the receiver and keeping the invariable location of the transmitter, as well as calculating time interval Δt_1 between the consecutive point ($n + 1$) and the previous point (n) and path difference Δl_1 between those points.

In practice, the increase of fracture and defects causes spectrum shift towards lower frequencies. Hence, near the transmitter with the frequency of 22 kHz, in the wall with continuous structure and distance of approx. 0.5 m, the amplitude assumes the maximal value for the frequency $f_r = 20$ kHz. Alongside with the increase of discontinuities, the frequency for maximum amplitude decreases and assumes the values of $f_r < 8$ kHz in the case of cleavage fracture.

While measuring time interval, the following is calculated:

– average phase velocity of wave, m/s:

$$\overline{C} = \frac{1}{n}\sum_{i=1}^{n} C_i \tag{1}$$

where:

C_i — wave velocity in a given measurement, 10^3 m/s,

n — number of measurements;

– standard deviation of velocity:

$$S_c = \sqrt{\frac{1}{n-1} \cdot \sum_{i=1}^{n} \left(C_i - \overline{C}\right)^2} \tag{2}$$

– variation index of longitudinal wave, %:

$$v_c = \frac{S_c}{\overline{C}} \cdot 100\% \tag{3}$$

Average compression strength of concrete in the construction reduced to the cube with the side of 150 mm was determined from the equation:

$$f_C = \overline{C}\left[a\overline{C}\left(v_c^2 + 1\right) + b + \frac{c}{\overline{C}} \right] \tag{4}$$

where:

f_C — average compression strength of concrete in the construction, MPa,
$\overline{C}$ — average phase velocity of wave, 10^3 m/s;
vc — variation index of longitudinal wave, %;
a, b, c — empirical parameters determined on the basis of laboratory tests of samples taken from the lining brickwork

Ultrasonic testing was carried out at 11 different levels of the shaft in the zones, where reinforcement was implemented. Average compression strength for the analyzed section of the shaft was f_C = 36.21 MPa, however the values for particular levels varied in the range 29.62÷40.27 MPa and variation index of strength v_R = 0.77÷13.45%.

On the basis of ultrasonic testing it was concluded that the concrete applied seems to fulfill the requirements set in the strength class C30/37. In individual measuring points, the analyzed concrete fulfils the requirements of the class C25/30, which may result from the fact that the ultrasonic tests were carried out also in the places of repaired damage, which must have affected the final results. The study of shaft lining seems to prove that the applied protective measures have been successful and allow for further shaft sinking.

4. Summary

The above considerations lead to the following conclusions:

1. Shafts in underground mines play an important role in the process of winning mineral resources. In Polish conditions, the period of shaft functioning usually oscillates between 30 and 50 years, hence the design and construction of shafts must fulfill highest technical requirements.

2. There are numerous methods of protecting walls during shaft sinking, including concrete lining, reinforced concrete lining, brick lining or tubbing. In unfavorable geological or mining conditions, like water content, local rock mass weakening, tectonic disturbance or influence of former exploitation, standard lining should be additionally reinforced.

3. In the analyzed case of shaft lining damage caused by washing out the soil from behind the lining it was necessary to apply sealing injections in all perimeter of the shaft and along all damaged section. The quantity of injected material was irregular in particular shaft levels. It also changed on the shaft's perimeter, where it could range between 0 to 3,000 kg even in the neighboring holes.

4. Mechanical parameters tests, i.e. cohesion, internal angle friction and water content, indicated considerable variation. Although the samples were collected from four directions at one level, there occurred even twice the differences of the parameters mentioned above. Cohesion most frequently ranged between 400 and 600 kPa, internal friction angle was in the range 17÷24° and water content – between 9 and 14%.

5. A detailed analysis of results obtained during laboratory studies of soils allowed determining the relationship between internal friction angle or cohesion and water content. The relationships described separately for sandy clay and for marly silt indicated correlation at the level of 60÷78% in the case of dependence angle of internal friction from water content. The obtained results allow keeping track of changing mechanical parameters of soils depending on water conditions.

6. The determination of rock mass properties around the shaft helped to select proper technology for increasing shaft lining stability. Anchors in the analyzed case successfully reinforced the surrounding rock mass and increased the bearing capacity of the shaft lining. Ultrasonic tests of shaft lining indicated concrete strength at the level of 36 MPa, which corresponds to the concrete class C30/37 and remains in accordance with the shaft design.

References

Bruneau G., Tyler D.B., Hadjigeorgiou J., Potvin Y., 2003. *Influence of faulting on a mine shaft - a case study: part I - Background and instrumentation*. International Journal of Rock Mechanics & Mining Sciences 40, 95-111.

Bulychev N.S., 2008. *Analytical design method for vertical shaft lining*. Arch. Min. Sci., Vol. 53, No 3, p. 371-382.

Wyllie D.C., Mah C.W., 2004. *Rock Slope Engineering*. 4th edition. PRC Press. 431.

Hartman H.L. (Ed.), 1992. *SME Mining Engineering Handbook*. Society for Mining, metallurgy, and Exploration, Inc. Littleton, Colorado, 2260.

Majcherczyk T., Niedbalski Z., Kowalski M., 2012. *3D numerical modeling of road tunnel stability – The Laliki project*. Arch. Min. Sci., Vol. 57, No 1, p. 61-78.

Ortlepp W.D., Joughin W.C., Ward A.K., Thompson J., 2008. *Reinforcement support of concrete shaft lining in Westonaria formation lava in the Ezulwini vertical shaft system*. 6th International Symposium on Ground Support in Mining and Civil Construction, Cape Town, South Africa, 561-580.

Pariseau W.G., 2007. *Design Analysis in Rock Mechanics*. Taylor & Francis Group, 560.

PN-G-05015, 1997. *Szyby górnicze – obudowa – Zasady projektowania* [Mine shafts - Lining - Principles of designing]. Polski Komitet Normalizacyjny. Warsaw, Poland, 21

Sadaghiani M.H. Bieniawski Z.T., 1990. *Geotechnical design of mine shafts*. The 31th U.S. Symposium on Rock Mechanics (USRMS), June 18-20, 1990 , Golden, Colorado. A. A. Balkema, Rotterdam, 823-830.

Vergne J., 2003. *Hard Rock Miner's Handbook*. 3th edition. Mcintosh Engineering, North Bay, Ontario, Canada, 314.

Wichur A., 2005. *State of stress and displacement of an elastic shaft lining caused by an axial-symetrical non uniform load perpendicular to the surface of the tube*. Arch. Min. Sci., Vol. 50, No 2, p. 251-270.

Wichur A., 2007. *Uwagi o projektowaniu technologii zamrażania górotworu dla potrzeb głębienia szybów* [Remarks on designing technologies of rock mass freezing for the needs of shaft deepening]. Górnictwo i Geoinżynieria 3. Krakow, Poland, 447-458.

Received: 17 January 2013