IN-DEPTH MONITORING – DIRECTIONS OF DEVELOPMENT AND THE PRINCIPLE OF UNIQUENESS

MONITORING WGŁĘBNY – KIERUNKI ROZWOJU I ZASADA UNIKALNOŚCI

Kamil Piróg - „Poltegor-Instytut” Instytut Górnictwa Odkrywkowego, Wrocław, Poland

The article presents the in-depth monitoring system, its components and practical applications. Part of the article is devoted to new directions of the system development and the main principle of designing it – the principle of uniqueness. A short characterisation of the behaviour of the rock mass at risk of landslide and the impact of this behaviour on the system's work has also been made.

Keywords: in-depth monitoring, landslides, waste bank

W artykule przedstawiono system monitoringu wgłębnego, jego elementy składowe oraz praktyczne zastosowania. Część artykułu poświęcona jest nowym kierunkom rozwoju systemu oraz głównej zasadzie obowiązującej przy jego projektowaniu – zasadzie unikalności. Dokonano również krótkiej charakterystyki zachowania się górotworu zagrożonego osuwiskiem i wpływu tego zachowania na prace systemu.

Słowa kluczowe: monitoring wgłębny, osuwisko, zwałowisko

INTRODUCTION

Within the SLOPES project co-financed by Research Fund for Coal and Steel and Polish Ministry of Science and Higher Education, in years 2015-2018, new technologies for monitoring and analysing threats of mass movements in lignite opencast mines were implemented and practically tested.

The works was carried out by an international consortium from six European countries lead by University of Nottingham. Within the consortium participated the following entities: “Poltegor – Institute” Institute of Opencast Mining, Exeter University, Geocontrol (Spain), VUHU (Czech Republic), Subterra (Spain), CERTH (Greece), INERIS (France).

During the project, research tasks were carried out in opencast mines located in Poland (KWB Bełchatów), Czech Republic (Most basin), and Spain. These works were focused on the implementation of various monitoring systems of rock mass displacements, collection and processing of measurement data obtained from them.

The cooperation between “Poltegor-Institute” and Ineris resulted in creation of an intelligent warning system against landslides in the KWB Bełchatów mine. The system collects measurement data from in-depth monitoring, informing about the risk of a landslide.

The article describes important issues regarding the development of the monitoring system, and the fundamental rules that should be followed when using depth monitoring.

PRACTICAL APPLICATIONS OF IN-DEPTH MONITORING

Due to the type of measurements, monitoring of rock mass displacements can be carried out using two methods, i.e. surface and in-depth methods. The first one and at the same time the basic one consists in registering changes of X, Y and Z coordinates on the surface with the use of traditional geodesy apparatus, or using, for example, photogrammetry. These methods are quick and proven, but they do not fully reflect the real conditions prevailing in the rock mass.

From a geotechnical point of view, measurements of displacements should be made in the area of the rock mass cut-off or in the area of the largest displacements. These usually do not occur on the surface of the studied area, but inside the soil medium, mostly on the contact layer with different physical and mechanical parameters (Abramson L., Willey J., 1996). Of course, the occurrence of weaknesses on the contact of geotechnical layers is not a rule. There may be areas of shearing determined by other factors, not excluding external ones in the form of dynamic loads due to machine movement. The origin of the landslide should be considered individually. The intention of the author of this publication is to emphasize the fact that despite various reasons for the formation of landslides, the area of shearing or flowing of the rock mass (displacement zone) always occurs inside the rock mass. Accordingly, there is a natural need to

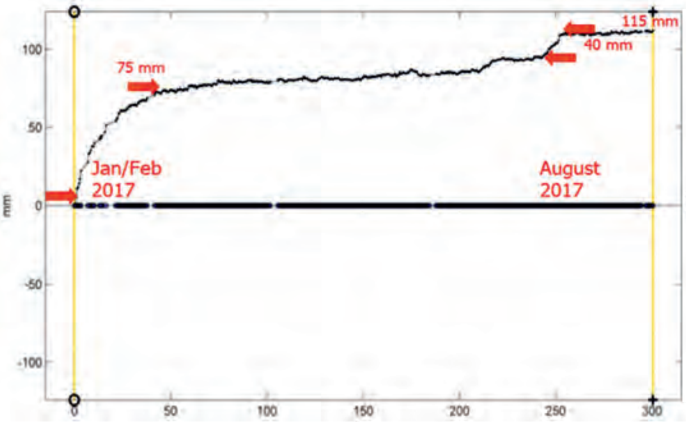


Fig.1. Rate of growth of rock mass displacements in the area of SAAF installation, Bełchatów

Rys. 1. Tempo przyrostu przemieszczeń górotworu w rejonie instalacji SAAF, Bełchatów

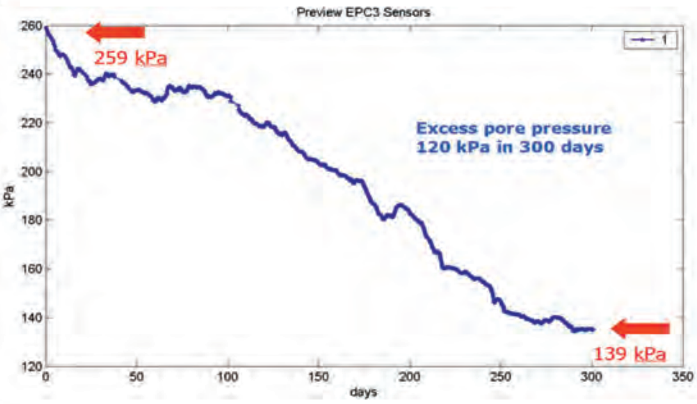


Fig.2. The values of the pore pressure of cohesive soil in the area of the SAAF installation

Rys. 2. Wartości ciśnienia porowego gruntu spoistego w rejonie instalacji SAAF

measure these displacements and the second measurement method is used for this, namely in-depth monitoring. In-depth monitoring, which includes various types of monitoring and measurement equipment, measures changes in the rock mass for the entire interval of geotechnical layers subjected to analysis (Stefanek, 2010). It is an expensive system due to construction and maintenance, but its important advantage is the ability to obtain information directly from the rock mass (in-situ measurements). Deep monitoring similarly to other types of monitoring has an observation function, but in combination with appropriate installations it can also perform a regulatory function (James H., 2006). From the point of view of rock mass mechanics, the regulatory function is a real tool for changing the physical parameters of the soil. From observations supported by measurements as part of the project, it appears that the movement of land exposed to mass movements is related to its humidity, i.e. the more the humidity deviates from the optimal one, the larger displacements are observed (Figures 1 and 2).

With regard to the installation in Bełchatów, the initial rate of displacement (up to the 40th day of measurement) was the largest and reached 75 mm. During this time, the highest pore pressure values were also recorded. Along with the reduction of the surplus of water in the ground skeleton, the rate of displacement stabilized as a result, the 200-day interval recorded a much smaller displacement, only within 10 mm.

This mechanism can be explained by the example of cohesive soils. Lowering the pore pressure in cohesive soils delays the moment of the gradual taking of load by water trapped in the soil pores. Thus, most of the load is taken over by the ground skeleton, delaying or completely reducing the moment of loss of stability.

The measurement of non-cohesive soils is carried out using open piezometers, while the adjustment of this parameter is possible through drainage wells. In relation to cohesive soils, the measurement of pore pressure is obtained by means of closed piezometers, whereas the adjustment of the above parameter using relief wells. The result of the moisture adjustment process is the reduction of the displacement pace visible at the depth measurements of the monitoring system. Therefore, the observation of the pace of displacements by means of depth monitoring may indirectly determine, for example, deviation of the humidity of the rock mass from the optimal one, and in the further process with the use of appropriate instruments it may be adjusted.

Thus, the ability to control the behaviour of the rock mass by regulating its moisture is extremely important, in particular in the aspect of deep mining excavations and hydrotechnical constructions.

A typical geotechnical instrument measuring the rate of displacement growth is the inclinometer or inclinometer integrated with a pore pressure transducer. Measuring points are usually located in the areas of the highest mechanical activity of the rock mass (the area of the rock mass cut-off). One of such places is the western slope of the Bełchatów Field, where, within the SLOPES project, a SAAF inclinometer with a pore pressure transducer was installed. The equipment has been working since December 2016, collecting measurement data for the system users on a daily basis and monitoring the behaviour of the rock mass in this mine region. During the current system operation, i.e. 22 months, a total of nearly 3000 measurements were collected. Since the SAAF system with a length of 100 m has MEMS type sensors deployed every one meter and a pore pressure sensor, this resulted in a total 201 records about inclination and pore pressure from a single measurement. Total number of 588,780 measurement data was received.

COMPONENTS OF THE IN-DEPTH MONITORING

The configuration of devices used for in-depth monitoring depends upon the complexity of the geological conditions and the nature of the facility. The simplest system consists of an open piezometer, i.e. a system for measuring the water level in non-cohesive soils. More extensive systems can also consist of closed piezometers, inclinometers, measuring units, drainage wells and unloading wells. Closed piezometers are responsible for measuring the height of the water table in cohesive soils. This is done by converting the pressure of the water being pushed onto the transmitter to the height of the water column. Inclinometers are technologically advanced systems used for direct measurement of displacements in the X, Y and Z directions inside the rock mass.

The combination of an inclinometer with a closed piezometer is defined as a measuring unit. They are very easy to use and interpret systems, as both displacement and pore pressure are measured at one point (Stefanek, 2010). In addition, they allow for the reduction of costs resulting from the installation of the unit in a single borehole. The monitoring and measurement equipment was made at the Bełchatów mine exactly in this way. As mentioned earlier, a SAAF inclinometer of Canadian production was installed in the borehole. It is an unusual structure since it consists of measuring segments connected by articulated joints, enabling the measuring system to be bent in any direction. The standard segment length includes three perpendicular inclination sensors with a tilt range of ± 45°, accuracy 0.02 mm/m, articulated joint error (azimuth) <±0.25°. In addition, the apparatus is equipped with a microprocessor soil temperature sensor. The system is waterproof and tested to 980 kPa, which corresponds to a 100 m water column.

The characteristic features of this system are as follows:

- length of measuring segments (i.e. displacement measurement interval): 0.5 m
- installation in a PVC protective pipe
- factory preparation and calibration of a given measurement string, and thus, no possibility of changing the length during installation
- the possibility of disassembly and servicing the system after installation in the borehole depends upon the size of displacements
- high flexibility resulting from the system design, a considerable range of its compression and tensile strength at the stage of work with the rock mass, allowing for a good representation of the deformation changes occurring in it
- much larger range of measurement of deformation in relation to probes installed in inclinometer columns
- large amount of measurement data and the ability to individually define the frequency and range of automatic measurements
- high accuracy of measurements, taking into account various correction factors, e.g. temperature influences, etc.

In addition, the system includes a pressure sensor for measuring pore pressures in cohesive soils made by Glotzl, type PP3RS, with the measurement range corresponding to the installation conditions. The sensor is installed in a sealed stainless-steel housing.

The data transmission station (HUB station) has been connected to the measuring devices installed in the borehole. It enables remote transfer of recorded data via the cellular phone network to the Internet and to the central server. The system is powered by high capacity batteries, recharged with solar cells. The central point of the station is the ‘data logger’, which performs the functions of collecting and transferring data via the GSM/GPRS modem and the cellular phone network to the Internet. The data obtained from the station are collected on the web server, where, with the use of specialised software, they can be edited in the form of graphs and tabular summaries.

The data transmission station with solar cells is installed

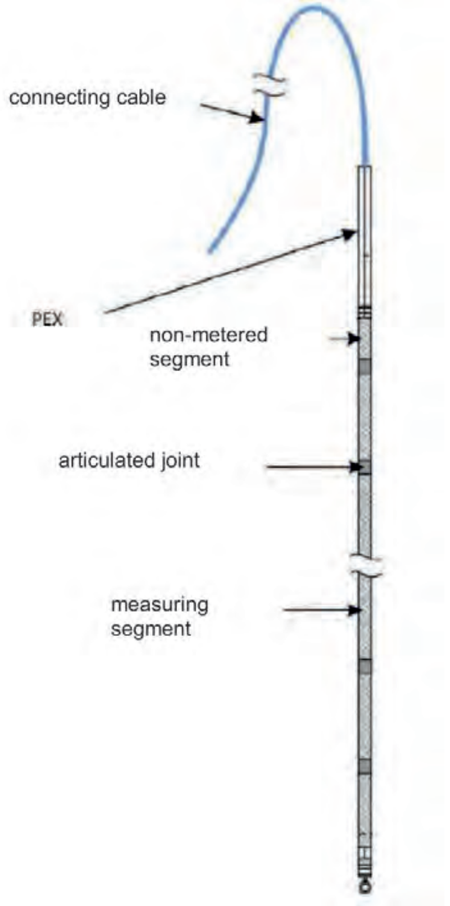


Fig.3. The schematic construction of the measuring chain
Rys. 3. Schematyczna budowa łańcucha pomiarowego

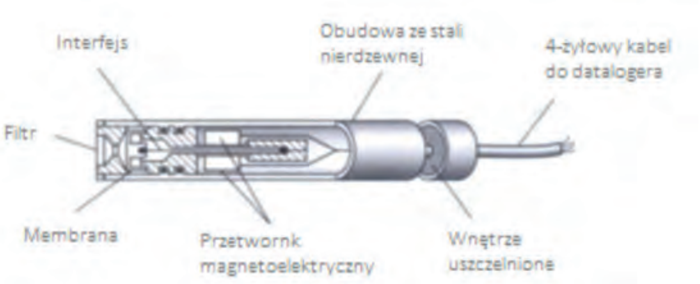


Fig.4. Diagram of the pore pressure sensor construction
Rys. 4. Schemat budowy czujnika ciśnienia porowego

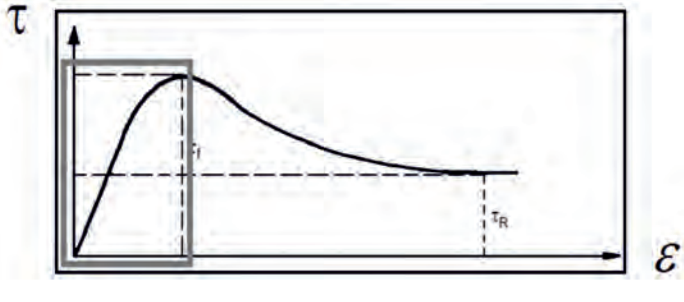


Fig.5. The behaviour of the waste bank in the stage of dynamic stabilization (Szymański, 2007)
Rys. 5. Zachowanie się zwałowiska w etapie stabilizacji dynamicznej (Szymański, 2007)

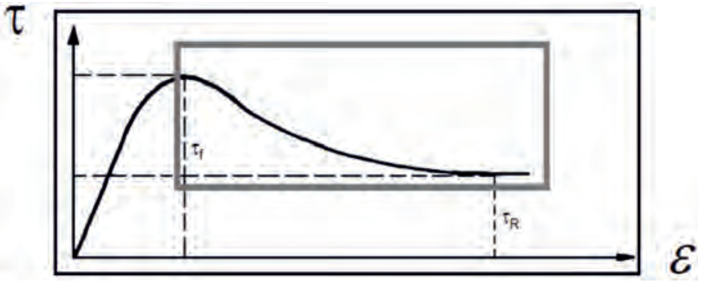


Fig.6. Landslide behaviour in the stage of the soil structure destruction (Szymański, 2007)
Rys. 6. Zachowanie się osuwiska w etapie zniszczenia struktury gruntu (Szymański, 2007)

on a mast with a height of 2.5 m attached to concrete spout measuring 0.5 x 0.5 m, above the borehole. Data collection systems are earthed and enclosed in a sealed housing made of weather-resistant plastic and protected with protective barriers painted visibly, with a size of 3 x 3 m.

THE BEHAVIOUR OF A ROCK MASS AT RISK OF A LANDSLIDE

The behaviour of the rock mass at risk of landslide largely depends on its physicomechanical properties. Generalising the above statement, one can come to the conclusion that in most cases the behaviour is categorised in three stages. These are the static stage, the stage of dynamic stabilisation and the stage of destruction of the soil structure (Stanisz, 2013).

The static stage is when there have been no displacements on a potential landslide within the last 50 years. Such a situation, in principle, never occurs in exploited earthworks. Only the second and third stages are distinguished there as a result of displacements due to changes in stresses caused by tipping, transporting and moving earth masses and other works causing dynamic loads.

Stress usually induces the formation of mass movements such as subsidence due to the consolidation of the soil. With respect to the slopes, they increase the sliding force, resulting in the deformation of the ground (stage 2, Fig. 1), and destruction of the soil structure after exceeding the maximum strength (stage 3, Fig. 2).

A characteristic feature of the second stage is the possibility of taking control over the behaviour of the rock mass. This is possible through the manipulation of drainage in a well-functioning in-depth monitoring system. Manipulation of drainage can improve two basic physical parameters of the soil – cohesion and internal friction angle. Reduction of hydration in cohesive soils increases the specific cohesion. The control of hydration

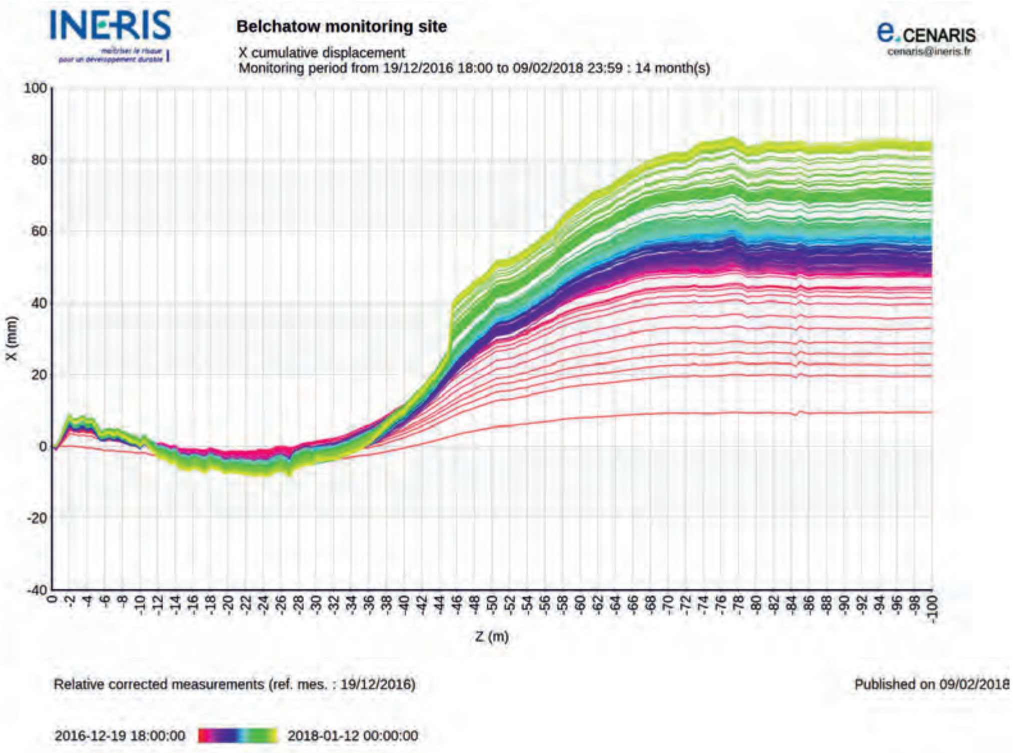


Fig.7. Rock mass displacement in the area of SAAF installation
Rys. 7. Przemieszczenia górotworu w rejonie instalacji SAAF

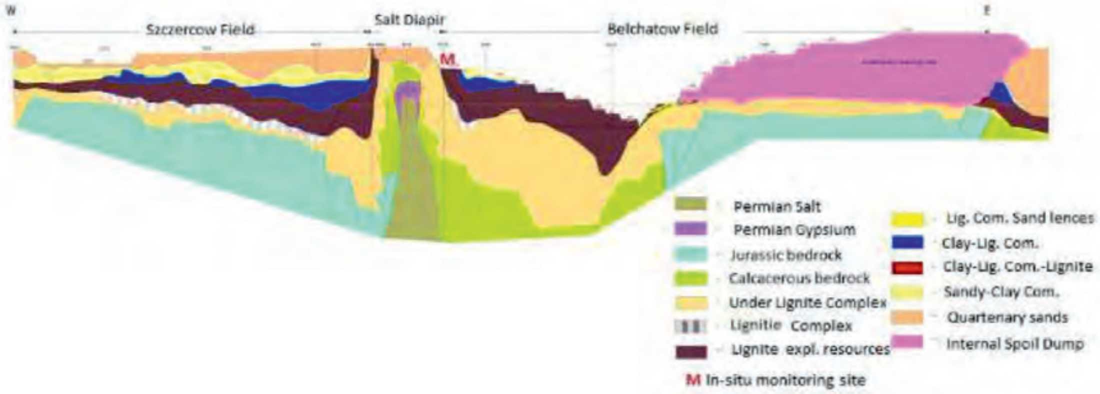


Fig.8. Synthetic geological cross-section through Bełchatów field and Szczerców field in KWB Bełchatów with the location of the monitoring station
Rys. 8. Syntetyczny przekrój geologiczny przez pole Bełchatów oraz pole Szczerców w KWB Bełchatów wraz z lokalizacją stacji monitoringowej

in cohesive soils and some non-cohesive soils allows them to achieve optimum humidity. It is the moisture that corresponds to the largest soil skeleton density (maximum internal friction angle). According to Terzaghi, these two basic parameters are decisive for the shear strength of the soil. After exceeding the maximum strength of the ground skeleton, it is destroyed. Then, the entire load is taken over by the water trapped in the ground skeleton. The third stage means the total lack of influence on the behaviour of the rock mass. This is a situation, in which in-depth monitoring is destroyed.

With reference to the western slope of the Bełchatów Field, where the measurement station has been built, the behavior of the rock mass indicates stage II. Diagram 1 shows the rate of dislocations of the rock mass with the marked shear zone at a depth of 45 m. During the system operation, the slope stability was not lost. The shifts visible on the chart are the result of natural and technological processes taking place in this area. Undercutting, dynamic loads caused by mining machines and, above all, geological structure - these aspects are of fundamental importance when interpreting the behavior of the rock mass.

DISADVANTAGES OF THE IN-DEPTH MONITORING SYSTEM

Among specialists in the field of monitoring and measuring equipment (MME), it is believed that currently, one of the biggest problems of in-depth monitoring is to maintain its measuring capability in the final phase of the dynamic stabilisation stage (area marked with a rectangle in Fig. 9.)

The analysis of the curve shows that after exceeding a certain value of the shear force (τ), the soil becomes more and more deformed (ε). The effect of this phenomenon is the accelerated operation of the MME. As we know, a damaged system is not suitable for use and should be rebuilt in order to continue the measurement. Unfortunately, this raises the system costs, and the measurement continuity is interrupted. Moreover, there are known places, where the installation of in-depth monitoring from a practical point of view is at least unfounded and even impossible. These are areas of particularly high geomechanical activity. Such areas are mine waste banks, where extremely high consolidation of the soil takes place, especially in the initial phase of forming the facility. Operation of in-depth monitoring would be disturbingly fast there, not to mention the difficulty of drilling a borehole in them. The mentioned above installation was made as a part of the SLOPES project and it is located on the exploitation slope, with a small displacement rate compared to those that can occur on the mine dumps. Vertical displacements on dumps reaching up to of 2 m/month are considered acceptable, thus assuming the maximum measuring range of the SAAF inclinometer of 0.5 m, one can easily come to the conclusion that the lifetime of the measuring unit would be about one week. This confirms that the inclinometer installation in this case may be unfounded.

DIRECTIONS OF DEVELOPMENT OF IN-DEPTH MONITORING

The development of in-depth monitoring takes place on many levels, for example in the field of materials science. The use is made of modern materials with characteristics that allow

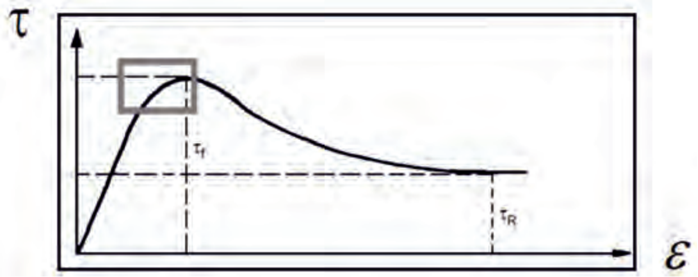
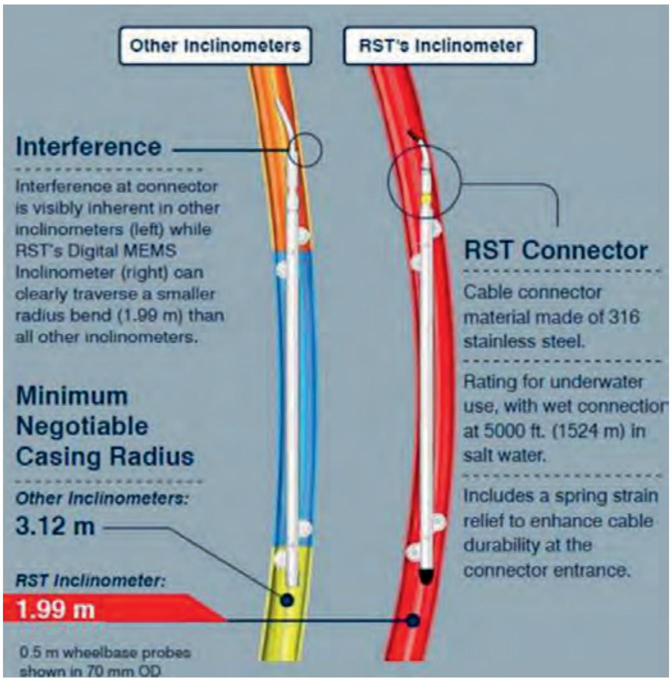


Fig.9. Area of accelerated destruction of the in-depth monitoring system (Szymański, 2007)
Rys. 9. Strefa przyśpieszonego niszczenia systemu monitoringu wgłębnego (Szymański, 2007)



Interference at connector is visibly inherent in other inclinometers (left) while RST's Digital MEMS Inclinometer (right) can clearly traverse a smaller radius bend (1.99 m) than all other inclinometers.

0.5 m wheelbase probes shown in 70 mm OD

Cable connector material made of 316 stainless steel.

Rating for underwater use, with wet connectio at 5000 ft. (1524 m) in salt water.

Includes a spring strain relief to enhance cable durability at the connector entrance.

Fig.10. Inclinometer tubes with a small radius of deflection
Rys. 10. Rury inklinometryczne o małym promieniu ugięcia

for the extension of the service life of the system. With regard to inclinometers, pipes with small deflection radii, resistant to displacement are used currently.

One should mention the rapid development in the field of automation of measurements and data transmission. The instrumentation installation technology has also been modernised. Currently, the fully grouted method is used for embedding inclinometers (Contreras, 2008). Taking the above into account, the disadvantage of in-depth monitoring is dictated by technological limitations that still do not allow for monitoring in areas with high geomechanical activity such as mine dumps.

The market of measurement instrumentation, shows that in the near future, fiber optics will play a large role in geotechnical measurements. Completely new technology can significantly reduce the cost of inclinometer, which can make possible to place them in geomechanically extremely active areas. It is already known today that the optical fiber measurement gives an unprecedented number of measurements. For comparison, the SAAF inclinometer has sensors measuring the displacement located every 0.5 m on a length of 100 m. The fiber optic inclinometer makes it possible to achieve a 5-cm measurement interval, so on a 100 m cut, there will be 2000 measurements. This is an unprecedented amount of information that can be obtained in this kind of measurements.

THE PRINCIPLE OF UNIQUENESS

In order to make in-depth monitoring more effective, i.e. to maximally extend its lifetime and obtain the highest possible measurement accuracy, it is absolutely necessary to adjust it to geological conditions, as well as the system of the facility development and the nature of displacements. This means that the system should be designed each time and therefore unique.

It should be considered that an improperly designed system will not work correctly and may mislead the future user and consequently, lead to a disaster. By applying the principle of uniqueness, the risk of unifying all facilities to the same category is minimised and the safety of their use increases.

During designing an inclinometer on the western slope of Bełchatów Field, it was necessary to recognize the ground-water conditions prevailing in this area. There is surface monitoring in the area, from which information on the rate of surface displacements can be obtained. Analysis of the current pace of surface displacements together with planned mining works may allow to estimate the volume of displacements in subsequent years. The measurement equipment installed in KWB Bełchatów is innovative, one of the first in Poland. It is characterized by high resistance to deflections in the X, Y, Z directions, which is directly submitted for longer life than traditional inclinometer apparatus based on PVC pipes. Unfortunately, the disadvantage of SAAF is the inability to expand the inclinometer and smaller measurement accuracy than in traditional inclinometers. Lower accuracy results from measurements based on algorithms, not on the direct measurement of length and angle as is the case in traditional equipment. Below is a comparison of traditional and new type inclinometer systems (Tab. 1).

The principle of uniqueness also applies to the method of system design in relation to the nature of dislocations in the area to be subjected to in-depth monitoring. In this case, the choice of the type of monitoring in terms of the method of measurement is very flexible, provided that appropriate instrumentation is used. There are following measurement methods:

- manual,
- semi-automatic,
- automatic.

Figure 11 shows the area marked in blue, in which measuring units (inclinometers with pore pressure transducers) have been installed with manual measurement.

In the case of an increase in the activity of the area, it is a good practice to rebuild the manual system for semi-automatic. In the scenario illustrated in Figure 12, in an area with increased geomechanical activity, within the yellow circle, inclinometers have been rebuilt in such a way that pore pressure measurements are transmitted automatically, e.g. every 6 hours. Based on the observations of the above parameters the measurement services can adjust the measurement intervals of manual inclinometer measurements. It should be added that manual inclinometer measurements are characterized by time-consuming measurements. Therefore, when the area reaches a high geomechanical activity, it is worth rebuilding the system / part of the system into fully automatic one.

This scenario is illustrated in Fig. 13. The area marked with a triangle is an area of high activity, with a preference for continuous monitoring.

Thus, it can be seen that the measurement area can be characterized by heterogeneity in terms of the severity of displacements and the monitoring adapted to it with different methods of obtaining data.

Tab. 1. Comparison of the functionality of inclinometer systems, source: www.measurand.com; www.rstinstruments.com
Tab. 1. Porównanie funkcjonalności systemów inklinometrycznych: www.measurand.com; www.rstinstruments.com

	SAA (Measurand)	**IPI (RST)**
Expansion possibility	No	Yes
Reuse possibility	**No**	**Yes**
Measuring accuracy	**±0.5 mm/m**	**±0.03 mm/m**
Possibilities of modifications during drilling	**No**	**Yes**
Measurement method	**Algorithm**	**Direct**

Fig.11. Area with low geomechanical activity
Rys. 11. Obszar o małej aktywności geomechanicznej

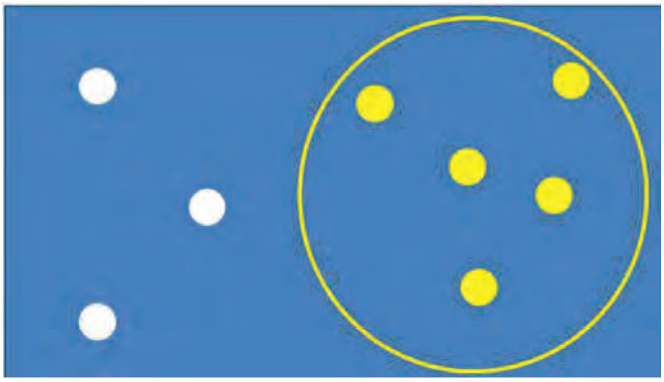


Fig.12. Areas with low and increased geomechanical activity.
Rys. 12. Obszar o małej i podwyższonej aktywności geomechanicznej.

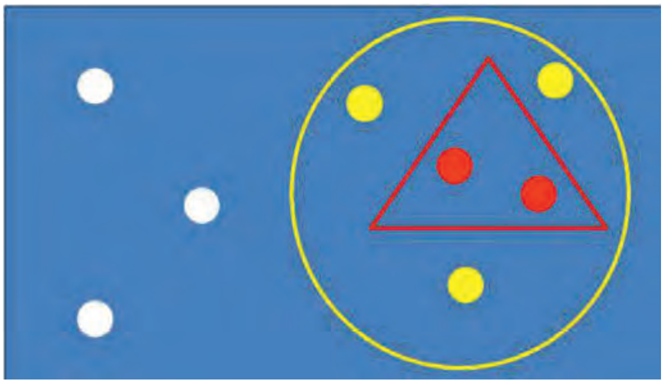


Fig.13. Areas with low, increased and high geomechanical actvity
Rys. 13. Obszar o małej, podwyższonej i dużej aktywności geomechanicznej

SUMMARY

To assess the threat of mass movements of areas of great economic importance or threatening the safety of people staying within their reach, it seems that the only correct solution is the installation of an in-depth monitoring system. Despite the construction and service costs, it offers much more control over the behaviour of the rock mass than the surface systems. An ideal situation is when the facility is equipped with both, surface and in-depth systems. In some situations, the surface system may not be sufficient to provide the desired safety, so it is good practice to use two systems, the more so because they complement each other perfectly.

In-depth monitoring is very precise, and new installation technologies make it more and more affordable. The technological development gives hope for widening its spectrum of applications, especially in areas with increased geotechnical activity.

When selecting in-depth monitoring, you must always take into account the conditions, in which it will operate. Following the principle of uniqueness, the system life is optimally extended, and an ideal cognitive field is created for conditions in the rock mass.

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Architectural details of Wrocław