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On-line landslide monitoring in lignite opencast mine

Surveillance en ligne des glissements de terrain dans une mine de lignite à ciel ouvert

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ABSTRACT: Geohazards occurring in Polish lignite opencast mines and spoil dumps are a common phenomena. Its mitigation is usually difficult due a high depth of exploitation, low strength parameters of prevailing clayey soils on the slopes. The paper present landslide investigations conducted inside EU SLOPES project "Smarter Lignite Open Pit Engineering Solutions" in Belchatow opencast mine. This mine, one of the largest excavations in Europe, with a length of 13 km, a width of 3 km and a depth of 310 is affected by numerous landslides. Geotechnical engineering investigations carried out for the project on the western slope of the mine included 100 m depth on-line inclinometer and pore pressure transducer at 30 m depth, index, strength laboratory tests. The monitoring measurements recognized magnitude of ground displacements of 150 mm at levels (+) 42 : (-) 58 m a.s.l., on the west slope of the mine. Obtained results implemented in numerical modeling should allow for better risk mitigation and early warning.

RÉSUMÉ: Les géorisques présents dans les mines a ciel ouvert Polonaises et les dépotoirs sont un phénomene courant. Leur atténuation est généralement difficile en raison d'une forte profondeur d'exploitation ainsi qu'en raison d'une faible résistance des sols argileux prédominants sur les pentes. Le document présente les enquetes sur les glissements de terrain menées dans le cadre du projet européen SLOPES «Des solutions intelligentes d'ingénierie pur les miens de lignite » a la mine a ciel ouvert de Belchatow. Cette mine, l'une des plus grandes excavations d'Europe, avec une longueur de 13 km, une largeur de 3 km et une profondeur de 310, est affectée par de nombreux glissements de terrain. Les études d'ingénierie géotechnique réalisées pour le projet sur le versant ouest de la mine comprenaient un inclinometre en ligne de 100 m de profondeur et un transducteur de pression interstitielle a 30 m de profondeur, tests de laboratoire de résistance. Les mesures de surveillance ont révélé une amplitude de déplacement du sol de 150 mm aux niveaux (+) 42 : (-) 58 m.s.l., sur le versant ouest de la mine. Les résultats obtenus mis en ouvre dans la modélisation numérique devraient permettre une meilleure atténuation des risques et une alerte rapide.

Keywords: mine-induced landslides, opencast mines, landslide monitoring, geotechnical site investigations

1 INTRODUCTION

Lignite opencast mining is assiociated with geohazards. This type of mining poses number of threaths due to the size and depth of the open-pit excavations in a number of European countries. In Germany, Poland, Czech Republic, Bulgaria, Romania, and Greece 433.8 million tones of lignite is mined every year. It still makes a significant contribution to the EU production of electricity.

The paper presents new on-line landslide monitoring system installed in the largest Polish opencast mine in Bechatow. In this mine up to

300 m deep exploitation and storage of very large masses of overburden at spoil heaps often trigger landslide processes. Its elimination is difficult or even impossible. The extent of risk is influenced by the geological factors, low soil strength parameters, land use, rainfall, fluctuations of groundwater levels, the use of explosives, seismicity, karsts, seepage and suffusion. The scale of potential failures can be large. Potential losses could cause risk for human life, exploitation efficiency and may adversely affect the environment. To gain a better understanding of the genesis of these processes, their scope, further activity and effective counteraction, the application of complementary research methods is of particular importance.

Presented research was carried out as a part of the EU RFCS SLOPES Project “Smarter Lignite Open Pit Engineering Solutions”. The project coordinated by the University of Nottinghan (UoN - UK) was conducted by an international consortium of six European parners (UK, Spain, Czech Republic, Greece, France and Poland). Project coducted by universities (Centre of Geomechanics UoN from UK, Cambrone School of Mines University of Exeter from UK), research institutes (VUHU from Czech Republic, CERTH from Greece, Poltegor-Institute from Poland), geotechnical companies (Geocontrol and Subterra from Spain) and mines (in Belchatow in Poland, Most in Czech Republic, Megalopoli in Greece, and in Aragon region in Spain) aimed at the practical implementation of modern monitoring methods in lignite opencast mining.

The SLOPES project included instrumentation, monitoring measurements, laboratory testing, numerical modeling and risk assessment programme. The open-pit soils and spoil dump samples obtained from various European mines were tested using modern laboratory eqipment including trixial and centrifuge apparatuses. This paper presents general description of lignite opencast mining monitoring methods and the selected results from the largest Polish lignite opencast mine obtained by the author inside the project.

2 OPENCAST-MINE MONITORING METHODS

For a better risk prediction and understanding of open-pit landslide genesis implementation of complementary monitoring methods has a special role. In each mine, there are three types of slopes: fixed slopes, delimiting the operating limits designed to obtain the license and after the slope is formed by exploitation it remains, unchanged for years, time slopes, which are created in the mining process, determining the current limit of exploitation, and spoil dump slopes for stored of overburden material. In order to determine the threats it is necessary to have detailed knowledge of geological structure and geotechnical conditions. Loss of slope stability could pose a risk to adjacent areas. In order to improve the reliability of geotechnical surveillance methods for each configuration, it is necessary to select appropriate testing and monitoring methods. This way size of the recorded displacements could be compared to those predicted earlier at the design stage. Good quality core drillings, laboratory tests, and numerical modeling could provide results that are close to the actual conditions in the mines. Important factors, influencing the stability of slopes of opencast mines are low soil strength parameters, the dipping of layers and pore pressure variations. Clays and others low strength soils or rocks are common in slopes and have a significant influence on the slope inclination design. Lignite mining requires relocation and storage of large masses of overburden on external or internal spoil dump sites. Transportation of clayey spoil dump soils by conveyor belt systems have negative influence on their strenght parameters. Mine drainage systems are influencing partial saturation of soils causing also significant changes in their strength parameters. A number of studies on this issue have been carried out in Great Britain (Bishop, 1973) and more recently elswhere (Nguyen at al, 1984; Steiakakis et al., 2009). Movement trigger mechanisms are usually very complex and time-dependent. This typically includes a range of complex geological factors as weathering, variations in stresses, seepage, moisture content and shear strength reduction. Opencast mine slopes contain a large number of silts and shale's, which can be disintegrated during wetting and therefore they have an increased amount of the fine-grained clay material. This may reduce their shear strength and make them more prone to high pore pressure variations which are one of the activating factors (Bednarczyk 2012, 2017, 2018). The effect of the destruction of soil structure and weathering processes over time are important factors to be taken into account especially in clayey soils and rocks subjected to repeated cycles of increasing moisture content and drying (Chowdhury et al., 1986; Ulusay et al., 1995).

3 POLISH ON-LINE SYSTEM

3.1 Localization

The mine is situated in central Poland, 30 km SW from the city of Lodz (Fig. 1). On-line field station was installed in Belchatow Mine on west slope of Belchatow in 4W risk area (Fig. 2).

3.2 Geological conditions

The mine is located in tectonic rift, formed in Mesozoic limestones and marls and filled by Neogene deposits. The thickness of the deposits within the rift is over 300 m, approximately 5-15 times higher than outside it. The main lignite seam is 20-60 m thick. Mesozoic blocks are separated along faults and dislocations. The mine leads the lignite exploitation on two operational fields, separated by a salt dome (Figs. 1-2). The largest volume of lignite is situated in deep secondary graben near the south slope of the rift. The most important landslide-prone structural surfaces are contacts of Quarterly and Neogene deposits, contact of Neogene clays and main lignite seam. Others preferable locations of movements are faults, cracks, tectonic and glacitectonic surfaces, low strength soils and varved Neogene clays. Landslides had volumes of a few hundred cubic meters to as much as 3 500 000 cubic meters, with displacements from a few millimetres to several meters over a 24 hour period (Rybicki 1996). The northern slope of this mine built of Quaternary low-strength varved clays posed numerous risks for conveyor belts transportation lines

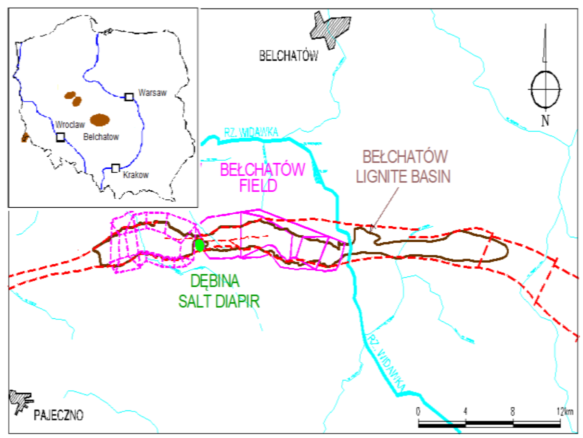

Figure 1. Location of the Belchatow Mine, Poland

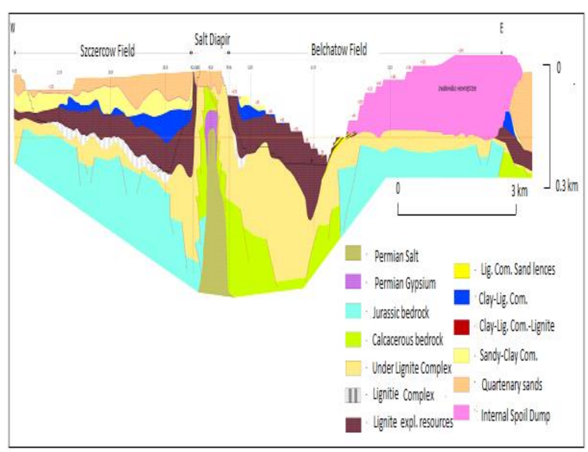

Figure 2. Geological W-E cross-section, Belchatow

Exploitation of Belchatow field will end in 2018, and at Szczercow field in 2038. In recent years, due to high depth of exploitation and neighboring salt dome structure, eight slope failure risk zones with active or expected landslides were reported on the west slope. This slope was selected for the investigations inside the SLOPES project.

New in-situ inclinometer and pore pressure instrumentation were installed at west slope of Bechatow field on the level +42 m a.s.l., 158-258 m below the natural terrain level (Figs. 3, 4).

3.3 System Specifications

The on-line monitoring system consists of the following devices:

a) 3D Shape Acellerated Arrays inclinometer system 100 m deep: 18 segments, 200 tilt sensors every 50 cm, 18 ground temperature sensors, 3 magnetometers for rotation control, total length of 100 m, measuring range: ± 45 deg.

b) Automatic pore pressure and temperature transducer, depth of 30 m, sensor type: piezoelectric with temperature sensor, measuring range 1.5 Bar, resolution: 0.025 %.

System is maintance free and powered by battery charged by solar pannel (Fig. 4). The GPRS on-line data are registered every 6 hours, starting from 19 December 2016.

Automatic measurements of various parameters directly affecting the slope stability allowing analysis of landslide activity and early warning. Detailed raports with monitoring results are continously delivered to the the mine owner.

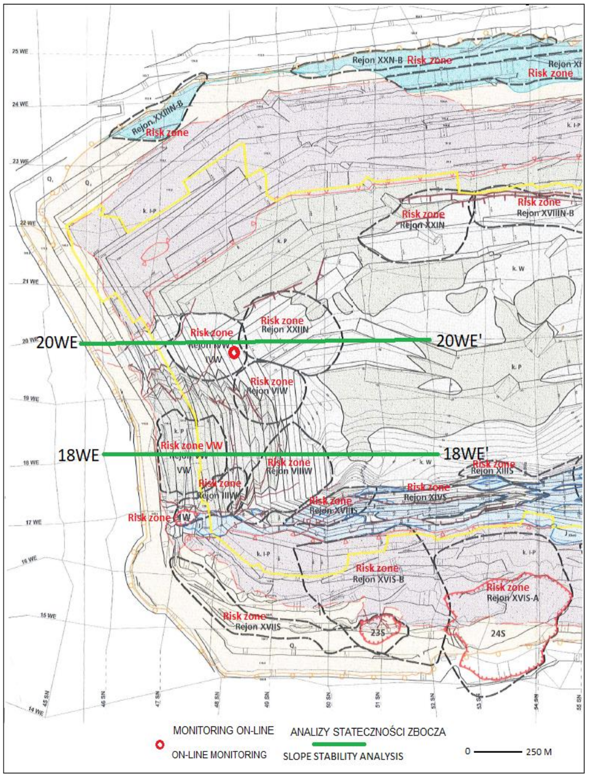

Figure 3. Location of investigations in Bechatow.

Figure 4. On-line system in Belchatow Mine

4 SITE INVESTIGATIONS

New instrumentation included 100 m deep, 132 mm core drilling. It was located at northern part of west slope in contact zone of the salt dome. The description of the core included soil type, moisture content, consistency and field tests of the soil strength parameters. For laboratory tests, 31 NNS undisturbed samples 90 mm in diameter and 500-700 mm in length were collected. The results of field strength penetrometer tests indicated that soil cohesion (C_u) varied 24-44.7 kPa. Undrained shear strength in vane test τ_f varied 23.9-47.8 kPa. The lowest values of these tests were recognized for silty clays at 54 m depth.

5 LABORATORY TESTS

The laboratory tests included index, direct shear, IL oedometer compressibility, triaxial CIU and CID tests. Grain size represents sandy silts, sandy loams, loams and loamy sands. Moisture content was the highest in loamy sands up to 32.8%. Relatively high moisture content was in loamy sand 17.2-28.8% and low in sandy loam 13.6-16.3%. The content of organic material was very high 3-19.3% with the highest 19.3%, registered in the deeper parts of the borehole at 82-92 m depth. The unit weight varied from 1.64 g/cm^3 for silty sand to 2.29 g/cm^3 for loamy sand. Respectively the dry unit weight varied from 1.23 g/cm^3 to 1.94 g/cm^3 for the same soils. Liquidity index varied from 0.17-0.37 for sandy loam with highest of 0.41 for sandy silt. Incrementally loaded oedometer compression test for silty sand characterized by the highest plasticity detected constrained modulus of primary consolidation M=1.74 MPa and constrained modulus of secondary compression M = 8.4 MPa. Strenght tests in shear box apparatus detected the lowest apparent cohesion of 19.5 kPa and apparent friction angle of 22.8^0 for sandy silts. Eleven triaxial CIU tests performed with consolidation and saturation in steps (with control of pore pressure parameter B) detected the lowest strenght parameters a depth of 46 m at sliding surface. At this depth effective cohesion of 18.7 kPa and effective friction angle of 9.8^0 in clays were detected. The highest strength parameters occred in lignite at 33.5 m depth. It has effective cohesion of 200 kPa and effective friction angle of 19^0.

6 MONITORING RESULTS

The monitoring indicated that the largest displacements over 150 mm were observed to a depth of 45 m (Fig. 5). The values of initially observed pore pressures of 258 kPa at 30 m depth dropped significantly to 50 kPa (Fig. 6). The largest magnitude of dispacements were registered in Jan. / Feb. 2017 - 70 mm, Aug. 2017 - 40 mm and May / Sep 2018 – 40 mm (Fig. 7). The movements were observed in the periods of pore pressure drop. The displacements in deeper layers were probably caused by complex factors including uplift of the coal seems by the salt dome.

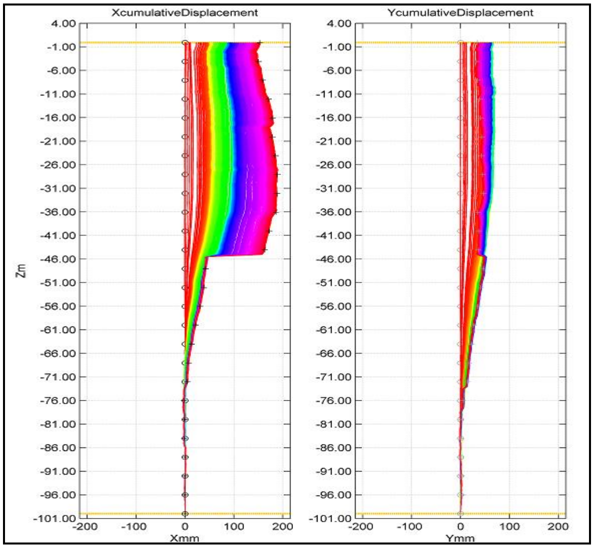

Figure 5. On-line cumulated displacements [mm]

The obtained landslide data were used to determine the threshold value of alarm warnings, and to study interactions between displacement and pore pressure data. The alarm setting was defined using previous alarm setting from the mine as 30 mm a day. However, this was not observed until August 2017.

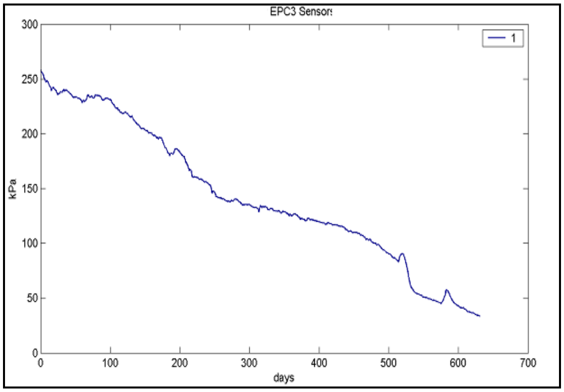

Figure 6. On-line pore pressures [kPa]

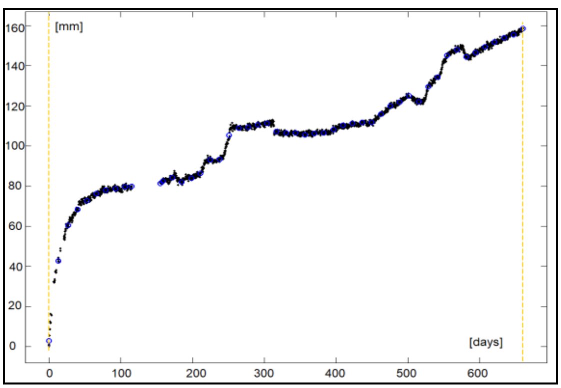

Figure 7. On-line magnitude of displacements [mm]

7 NUMERICAL MODELLING

Numerical modelling was performed in two cross-sections 18 and 20 WE. Implemented SSR method tends to reflect the actual condition on the slopes leading to the reduction of shear strength of soil till to stage of losing stability. Mohr-Coulomb elastoplastic strength model required specification of bulk density, effective cohesion and effective angle of internal friction. The principles of classification recommended by the Eurocode 7 (CEN 1994) introduced general concepts in geotechnical design. It includes derived characteristic and design values of effective strength parameters from so-called comparable experience (Kulhavy 1992, Phoon et al 1999). The strength parameters used for the calculations presented in table 1 were assumed on the basis of corrected values from previous investigations and modeling (Bednarczyk 2017). For Mesozoic rocks, parameters were specified using GSI Marinos, Hoek 2005 classification. The obtained values of factors were ranging from 0.85 in cross-section 20WE to 1.14 in 18WE (Fig. 9).

Figure 8. Landslide near the cross-section 18WE.

Table 1. Soil / rock strength parameters

Soil/rock type	**ρ [kg/m^3]**	**c'[k Pa]**	**φ' [º]**
Soil /rock type	ρ [kg/m^3]	c' [kPa]	φ' [º]
Sand (Q)	1850	1.0	30.0
Glac. Loam (Q)	2180	40.0	9.16
Silts (Q)	2130	40.0	15.00
Clays (Q)	2080	80.0	5.33
Clays (N)	2110	89.0	5.81
Lignite (N)	1180	170.0	14.80
Sands (N)	1950	1.0	32.00

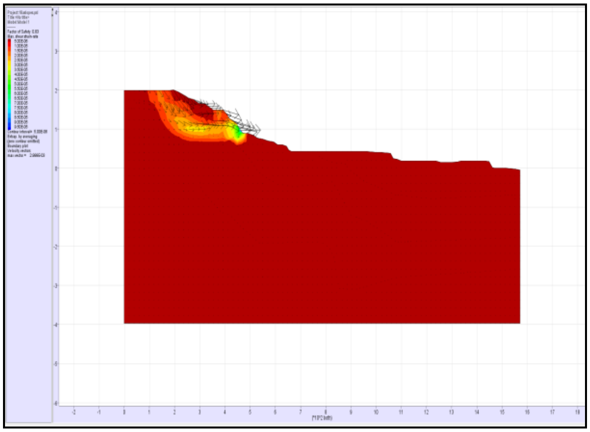

Figure 9. Slope stability modelling 18WE, FoS=0.83.

8 SUMMARY AND CONCLUSIONS

New, the first in Poland landslide on-line monitoring system was installed in Belchatow Open-pit Mine. High risk region on the west slope of the mine was equipped with 100 m deep instrumentation. Modern monitoring eqipment provided new displacement and pore pressure data. Displacement magnitude up to 155 mm to a depth of 45 m were registered in 22 months time. At the same time the pore pressure drop from 260 kPa to 50 kPa. The conclusions indicated that excess of pore pressure was pernamently caused by mine water pumping system. The slope was characterized by low factor of safety FoS = 0.83-1.10 that was detected by numerical modelling. On-line system allowed early warning. Data will be used to study landslide triggering factors.

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