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Ground Displacement and Seismic Risk in a Brown Coal Mine

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ABSTRACT

Mining operations in the largest Polish brown coal opencast mine in Belchatow have often been accompanied by slope failures. The localization of the mine in a tectonic rift structure, tectonic stresses, faults, karst processes and salt intrusion near its western border together with loads of external embankments have caused numerous seismic shocks. Several shocks of a magnitude stronger than M=4x10^{8}J have caused some small damage to nearby buildings. The Central Mining Institute registered epicentres in limestone bedrock at depths of 1.5 km. Some shocks probably influenced ground movement activation. The largest landslides were up to a few Mm^3 and there were displacements of 2mm-2m per day. The author performed investigations including monitoring, in-situ, laboratory tests and modelling. One of the largest landslides occurred on the south slope. The interpretation of soil parameters was complicated due to partial saturation and preconsolidation of clayey soil. Remediation included unloading the upper part of the slope. However, in a mine of this size and type, it is difficult to reduce risk.

Introduction

The largest Polish opencast mine and one of the largest in Europe is located in the central part of Poland, 40 km south of the city of Lodz (Fig. 1). A lignite deposit is situated in the Kleszczow Tectonic Rift Valley, which is approximately 30 km long and 2 km wide. It is characterized by a general S-E direction and is divided into two exploitive fields, Belchatow and Szczercow. The Belchatow Mine, operated by the PGE Company, has a total length of 12.5 km, width of 3 km and a depth of 310 m with coal resources of 2 billion tons. The exploitation of 38.5 million tons a year requires the removal of overburden by mining excavators in the average amount of 100-120 Mm^3 per year. The nearby PGE Power Plant has a capacity of 4320 MW.

Figure 1. Bechatow mine localization, OPGK Warsaw (1996)

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Dynamic loads caused by shocks can have an influence on landslide activation. The author of this paper had the opportunity to investigate one of the Belchatow Mine landslide regions using piezocone tests. These tests were performed in the mine 50m below the ground level in overconsolidated, partially saturated CL clay. The results of these investigations, laboratory tests, monitoring, numerical modelling methods, characterization of seismic conditions and landslide remediation methods are presented in the paper.

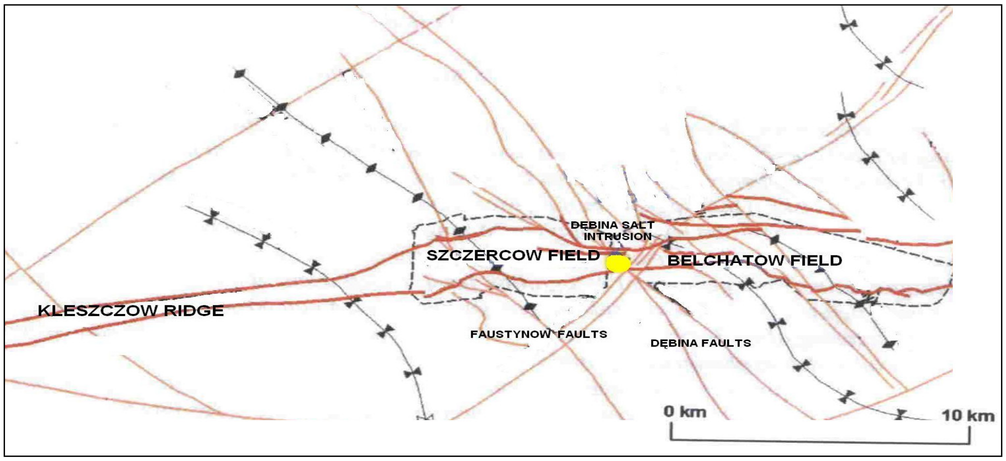

Figure 2. The Belchatow Mine exploitation fields and tectonic structure (Kurpiewska 2013)

Geological and Geotechnical Engineering Conditions

Geotechnical conditions are influenced by the localization of lignite deposits in the tectonic rift valley. This relatively young Neogene and Quaternary-age graben is characterized by a complex structure. Its bedrock layers are built of weathered Jurassic and Calcareous limestone and marls that have been subjected to karst processes. The occurrence of tectonic stresses in the bedrock has caused numerous seismic shocks. Two main border faults are located in the north and south sides of the mine. The western parts of the mine have the most complicated tectonic structure. This part of the rift valley is cut by faults that are oriented NW-SE and NE-SW (Fig. 2). Difficulties in coal exploitation were also caused by Debina salt intrusion located between the Belchatow and Szczercow fields. This structure influenced the state of the stress, uplift of the terrain, groundwater conditions and landslides of a few thousand to few million cubic meters. Secondary deep graben is located in the south-western part of the Belchatow field. It is characterized by the highest thickness of brown coal deposits and a high mass movement hazard in the coal mine, which is 200 m deep. Due to the layers’ consequent dip and paleolandslides, during the past 30 years, mining operations have been constantly accompanied by landslides activated on structural surfaces on the south slope of the mine. These regions were built with low-strength Neogene clay soil near the deep secondary-level rift structure. Other landslides were observed in Quaternary clay located on the north slope.

Seismic Conditions

The very complex tectonic structure of the rift valley influences seismic conditions and directly affects stress-strain relations. The mine is situated in an area that is characterized by several generations of faults. The first and oldest generation of east-west oriented faults defines both sides of the rift. The south marginal fault dips north of 35-70°. The north fault forms a natural Quaternary erosion zone. In some areas, these faults form trench zones composed of several parallel faults. The second generation of faults are oriented N-S and NE-SW. They cut the trench structure into smaller blocks. The third generation includes faults in a NW-SE direction (Figs. 2, 3). The seismic activity was a big surprise for the mine and for seismologists. The strongest observed shocks had a magnitude (M) ranging from 4.0 to 4.6 (10^9 - 10^{10}J). These factors had a strong impact on the environment and posed a threat to the safety of mining processes. Some smaller dynamic loads were also caused by blasting stiff hard workable rocks. The seismological network in the Belchatow Mine was installed in 1980 by GIG Central Mining Institute in Katowice, Stec & Jonczyk (2004). It allows for the continuous monitoring of seismic activity and long-term analysis of the origins and nature of seismic processes occurring in the mine. The location of shocks, epicentres and magnitude and energy of the events can be estimated. Seismic shock localizations are presented in Figure 3.

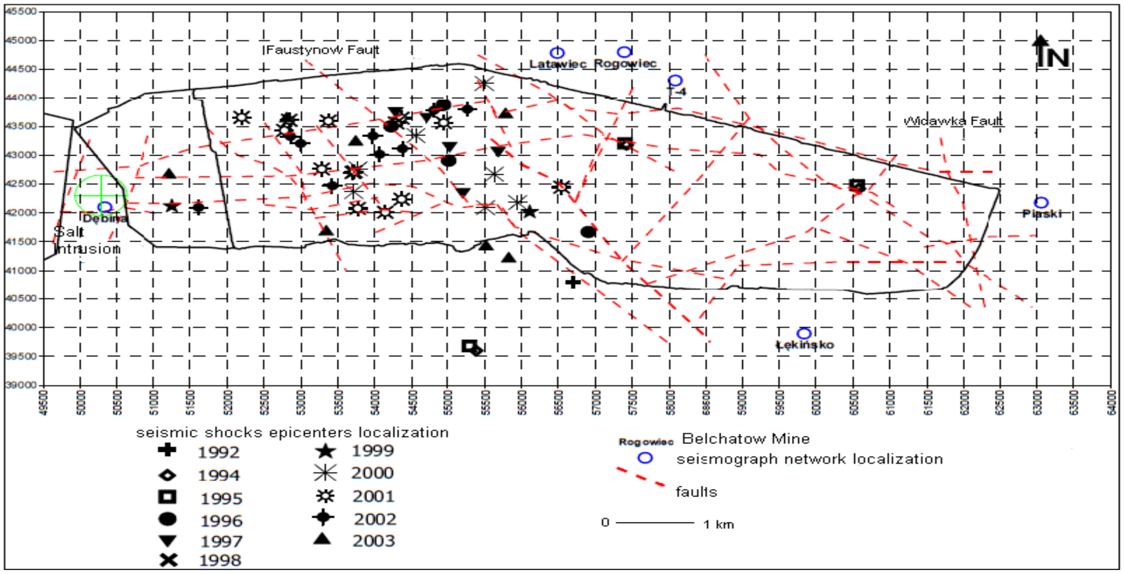

Figure 3. The localization of seismic shock epicentres 1993–2003, Stec & Jonczyk (2004)

The localization of seismic shock epicentres and changes in their position in time depend on the westward movement of mining exploitation. The results confirmed that the shocks were caused by mining operations' disturbance of the stress equilibrium. These changes were caused by the drainage of groundwater, removal of overburden and influence of coal exploitation. The removal of overburden and its external and internal storage caused offloads in some places and new loads in other locations. Drainage caused variations in mechanical properties of the soil and its partial saturation. These phenomena probably initiated dynamic processes in fault zones which were characterized by a natural stress concentration. In regions of shock outbreaks, the tectonic structure was very diverse. Based on previous observations, it was expected that seismic shocks of energy stronger than $E = 10^8$ J and a vibration acceleration of more than 250 mm/s^2 could cause minor damage to buildings near the mine, resulting in cracks in their walls. In the years 2001–2009, local residents submitted up to 531 applications for compensation of damages to the buildings, according to Dziennik Lodzki (2014).

Table 1. Examples of seismic shock in the Belchatow opencast mine

Date	Energy [J]	Magnitude [M]
29-11-1980	10^{11}	4.66
17-01-1985	3.6×0^{10}	4.60
28-11-1992	1.1×10^{10}	4.34
08-06-2004	2.99×10^{9}	4.04
30-05-2005	7.93×10^{9}	4.26
22-01-2010	1.61×10^{10}	4.42
30-11-2014	1.37×10^{10}	4.40

Landslide Characterization

The main mass movement risk was observed on the south and north slopes of the mine built of Neogene-age paleolandslide and paleoalluvial fan deposits. Landslides on this slope were often activated on structural surfaces in clay located above the coal deposits. Examples of some of the largest landslides registered on the south slope are presented in Table 2.

Table 2. Examples of landslides registered in the Belchatow Mine, Jonczyk, Organisciak (2010)

No. Slope, Line	Date	Vol. [Mm^3]	Type, range level [m.a.s.l.]	Slip surface direction	Risk posed
15S South, 84-85	Jun. 1988	1.5	structural +74/-20	5-20°/ NW in bottom of coal	surface and internal drainage, fire risk
20S South, 64-66	Feb. 1997	2.5	structural +205/+72	7-9 °/ NE in weathered Calc. marls	risk for south slope power supply line, water pump station
22S South, 65	Mar. 2005	0.65	structural +80/-15	5-20 °/ NW in Neogene clayey-sands	risk for south slope, landslide tongue over coal deposit
24S South, 52-54	Dec. 2005	3.5	structural +199/+119	4-15 °/ N in clay and coal	risk for power plant, 11 drainage systems

Monitoring Measurements

Different types of geotechnical investigation methods were implemented by the mine. It included inclinometers, piezometers, surface displacements, a seismic monitoring network, a CPTU test, laboratory tests and numerical modelling. To detect and prevent risk, a network of 22 inclinometers reaching a depth up to 100 m. was used (Jonczyk, Organisciak 2010). Starting in

1999, ground displacement monitoring has been conducted a few times per year. It has increased the safety of mining operations. However, some of the installations have been damaged by large displacements at shallow depths of 10–15 m, as in inclinometer 3S on the south slope (Fig. 4).

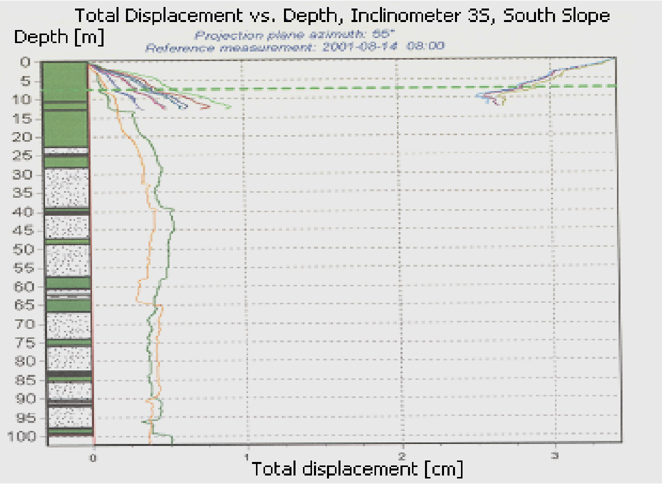

Figure 4. Inclinometer measurements, south slope of the Belchatow Mine

Table 3. Categories of risk zones in the opencast mine (Kurpiewska, Wcislo, Czarnecki 2013)

Category I	Category II	Category III	Category IV	Category V
The largest scale, high threats to upper edges of the mine and outside for infrastructure, risk of damage to conveyor belts, long-term coal supply	Medium-scale threats to infrastructure and dewatering system, conveyer belts, power supply, roads, interruption of coal supply	Small scale threats, causing difficulties for mining operations	Areas dedicated initially to Cat. I, II, III after remediation works; however, the threat wasn't completely eliminated	Areas dedicated initially to Cat. I, II, III, or IV after effective remediation that improved stability, but the risk wasn't completely eliminated

The scope of remediation works depends on the risk zone category and level of geotechnical recognition. Potential risk zone categories were identified. The classification presented in Table 3 includes five categories of potential threats. Four levels of recognition of risk zones were defined: a) weak – by few documentary or hydrogeological boreholes, b) average – recognition in full documentation lines and boreholes, c) good – field mapping over the hazard zone, dedicated boreholes, d) very good – detailed field mapping, full recognition by core boreholes. The following critical values of displacement rates were specified for the identification of alert conditions using inclinometer and surface displacement data: i) initiation – 8–14 mm/day, ii) warning – up to 20 mm/day and iii) critical – ≥30 mm/day. At landslide 22S fort, the identification of various stages of the development of this landslide were specified using surface displacement data and four levels of alerts: i) initiation – less than 1000 mm, ii) warning – 1500 mm and iii) critical – 2000 mm. Surface displacement monitoring networks were located on the south, north and west slopes of the mine. Additional monitoring points were located near important infrastructure such as conveyor belts, ramps and pumping stations. Thirty-two risk zones were identified on the permanent slopes of the Szczerców field in 2012. These include fourteen category I zones, six category II zones and thirteen category III zones (Kurpiewska 2013). Examples of numerical analyses conducted by the author in previous years include in-situ investigations (Janecki & Bednarczyk 2000) and Z-Soil slope stability analysis for the south slope of the mine, which are presented in Figure 5. Field monitoring and in-situ data deliver data for slope stability analysis using Flac software (Rybicki, Flisiak 2007). Numerical modelling shows that in order to ensure stability for permanent slopes, the factor of safety F should not be less than F=1.3–1.5. These analyses implemented effective and residual parameters obtained from high quality CID triaxial laboratory tests. For the other mining slopes, F≥1.2 should be adopted to ensure minimal slope stability.

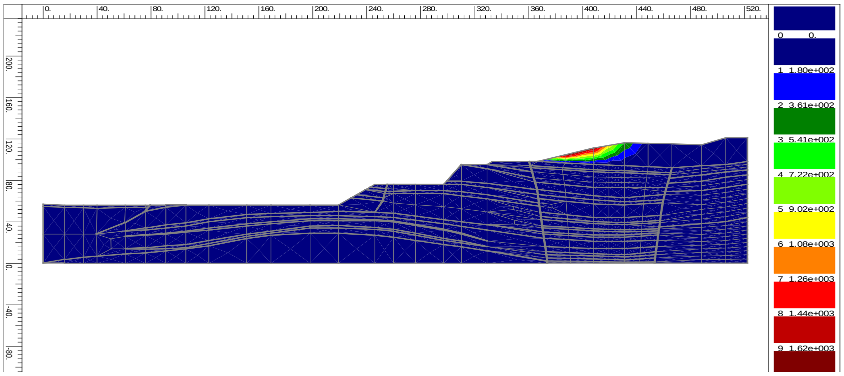

Figure 5. Results of FEM slope stab. analysis on the south slope of the Belchatow Mine, Fs=1.3

Field and Laboratory Tests

For the last twenty-five years, piezocone penetration tests with pore pressure measurements have been used for soil investigations in the mine. (Hysson 50 A.P Van Den Berg Penetrometer). The author of this paper had the opportunity to perform an in-situ CPTU and laboratory test interpretation near one of the largest landslides, 20S, on the south slope of the mine (Figs. 6, 7). The results of field and laboratory tests were used for recognition of the landslide area and for numerical modelling of slope stability. Thirteen piezocone tests were performed at sites 50 m below the natural terrain level west of landslide 20S. For better recognition of soil parameters, CPTU were calibrated using undisturbed clay soil samples for CID, CIU triaxial and IL (Lab 1) oedometer (Lab 2) tests.

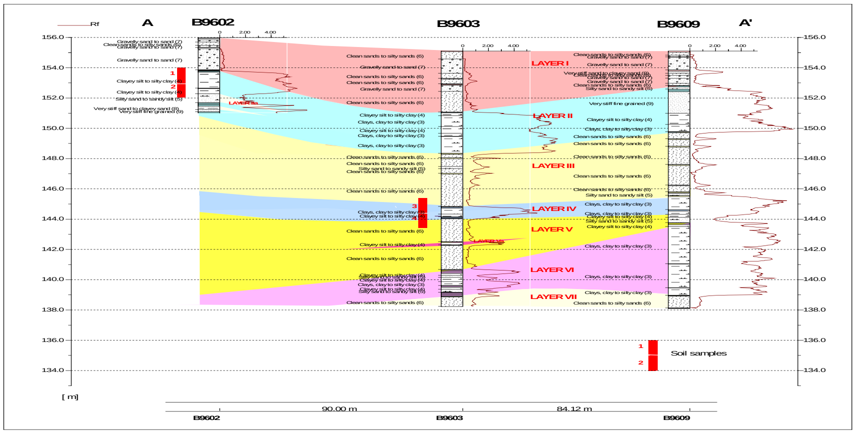

Figure 6. Geotechnical cross-section near landslide 20S based on CPTU tests (R_f MPa)

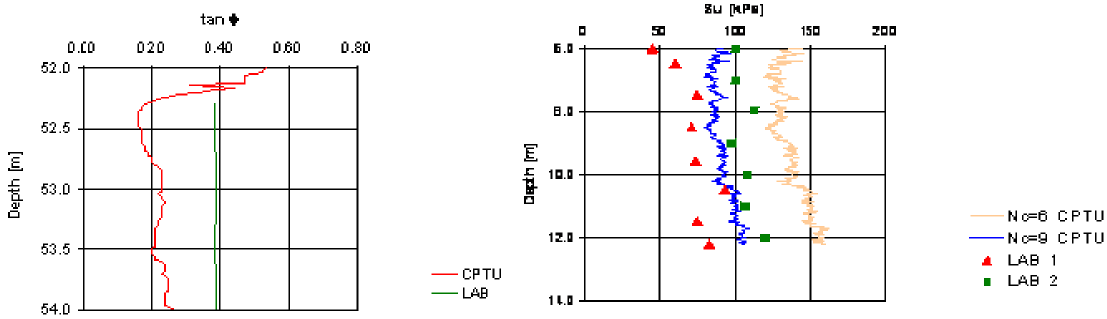

Figure 7. Friction angle and undrained strength in clay based on CPTU and laboratory results

Table 4. Results of CPTU and laboratory interpretation, Bednarczyk, Sandven (2004).

Parameter		Description
Soil type		Stiff clay to hard, stiff soil
Undrained shear strength	[kPa]	250–500
Preconsolidation pressure	[kPa]	500–600
Overconsolidation ratio	[-]	6–8
Compr. moduli in overcon. range	[kPa]	20 000–30 000
tan ϕ	[-]	0.2–0.4

Besides soil classification, test interpretations included the identification of the mechanical parameters of soil, such as total and effective shear strengths, compression moduli and stress history (Fig. 7). A summary of the results is presented in Table 4. A prediction of soil type and estimation of mechanical parameters were conducted using methods by Senneset, Sandven and Janbu (1989) and Robertson (1990). Analyses showed that a reasonably good comparison between field and laboratory test data could be obtained. An estimated value of the friction angle and cohesion in undrained tests for clay were: $\varphi=21.3^o$, c=8.56 kPa. In drained tests, the effective values of the friction angle varied from 8.1^o for clay to 25.1^o for sandy clay. Incomplete saturation of specimens due to the mine water pumping system complicated the interpretation of the results. These types of specimens require a special type of triaxial apparatus that allows for the measurement of air pressure inside the samples during tests. The friction angles measured during piezocone tests were therefore lower compared to the laboratory triaxial and oedometer test results (Fig. 8). Difficulties in interpretation were also caused by complex geological stress history.

Landslide Remediation

The procedure for landslide remediation depends on the risk category. High risk areas (cat. I, II, III) required a detailed design of remediation works. For the most serious threats, detailed recognition (cat. B, C, D) was performed for the safety of brown coal exploitation. Dewatering of the slip surface and syncline geological structures helped improve stability conditions. To prevent water infiltration, all fractures created on a slope were eliminated. One widely used method was changing the slope contour. Changes in the height and angle of the slopes depended on the hazard category. An improvement in stability was achieved by offloading the upper parts of the slopes or by supporting their lower parts with ground buttresses. However, these methods were expensive and brought a number of difficulties to mine operation. They also caused coal losses. Another option in the risk zones was the selection of mining operation speed and direction for partial unveiling and slow relaxation of the rock masses in order to prevent slope movement activation on determined slip surfaces. Restrictions were implemented that excluded pumping stations, transport ramps, conveyor belts, roads and high voltage power lines from risk regions. A necessary inclinometer monitoring network, systematic field observations and detailed mapping were implemented. At landslide 20S, which was investigated by the author, a slope inclination of 1:3.0 was changed to 1:3.5. The corrected inclination of the slope allowed 0.2 Mm^3 of brown coal to be reclaimed.. According to Jonczyk and Organisciak (2010), the remediation of landslide 24S on the same south slope included the movement of the edge of this slope 60 m to the south at a length of 1400 m by taking 4 Mm^3 of overburden. The most dangerous conditions were registered in the western part of the Belchatow field above the secondary deep rift near the south border of the mine. From 2006–2011, the protection of slope stability was implemented several times on the north, south and the west slopes of the Belchatow Mine.

Conclusions

Ground displacement and seismic risk in the Bechatow opencast mine are threatening coal exploitation. Different types of geotechnical investigations and monitoring were implemented by the mine in order to minimize risk. Numerical modelling, inclinometer and seismological monitoring and in-situ tests aided in the recognition of risk areas. However, caution should be taken because the in-situ tests should be carefully scaled in the laboratory tests, especially in case of highly overconsolidated and partially saturated soil. For this reason, special triaxial equipment for partially saturated specimens should be used. Additional research work and numerical modelling is needed in order to predict the seismic influence on movement activation. Although the mine has identified landslide triggers and remediation procedures in recent years, the elimination of landslide hazards in the mine is not possible. Sometimes the only way to counteract the hazards is to unload slopes prone to failure and have mining excavators decrease their inclinations. Comprehensive geotechnical engineering site investigation, monitoring and numerical modelling could significantly help mitigate hazards and increase mining effectiveness.

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