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Landslide risk in Polish lignite opencast mines and implementation of remote monitoring methods

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ABSTRACT: Landslides in Polish opencast mines pose a threat to the mining process and the surrounding areas. There are a number of potential triggers. The most important of these are the mine's location, geotechnical engineering conditions, depth and slope steepness. Remediation is complicated due to the large size of the landslides and the extent of the observed displacements. This paper presents examples of landslide investigations, monitoring, and countermeasures in the two largest opencast mines in Poland. It also describes the application of modern monitoring methods at the Bełchatów mine — the EU's largest excavation — as part of the EU project 'Smarter Lignite Open Pit Engineering Solutions'. This project was conducted by a consortium from six European countries. Eliminating the risk of mass movement is impossible. Therefore, detecting ground movements is very important. Improving our understanding of landslides and their triggers requires the application of complementary research methods. Modern monitoring methods, laboratory testing and modelling can help reduce the risk. The aim of this research is to evaluate how these techniques could be applied to reliably detect landslide movement. Particular focus was placed on in-situ monitoring, high-resolution satellite Persistent Scattered Interferometry (PSI), terrestrial laser scanning TLS, LiDAR laser scanning, numerical modelling and laboratory testing. The project results indicated that predicting and remediating landslides in Polish opencast mines is challenging. Each technique has its own advantages and disadvantages and requires in-depth research Experience from past events and the latest research could be used to reduce the risk and protect the effectiveness of exploitation and the environment.

KEYWORDS: Landslides, monitoring, remediation, mining.

1 INTRODUCTION

Lignite mining still makes a significant contribution to the production of electricity in the EU. In Germany, Poland, the Czech Republic, Bulgaria, Romania, and Greece, 300 million tons of lignite are mined every year (Eurostat 2022). The exploitation of deeper and deeper lignite deposits and storage of clayey overburden is constantly associated with landslides. They pose a risk for lignite exploitation efficiency; they also pose risks for the environment and adjacent areas (Azcue 1999). Over 2.5 billion tones of mined lignite in Poland were accompanied by the excavation and storage of over 9.5 billion tones of overburden. The Bełchatow Mine, one of the largest excavations in Europe, has been operating for over 40 years and has produced over 1 billion tones of lignite. Currently, the lignite exploitation takes place in two mining fields 200-300 m deep. The extracted lignite is delivered to the power plant, electrical capacity of 5298 MW (actually over 20% of Poland's annual demand). The volume of lignite extraction will be lowered from 30.1 mln in 2020 to 6,9 million tones in 2030. The Belchatow Field, which has dangerous slope stability problems, will be closed in 2026. The Szczercow Field will remain open until 2038. The Turow Mine, with annual lignite extraction of 7,5-10 millions of tones and is located in the SW part of the Lower Silesia region. It has a specific location close to the border with Germany and Czechia, between two rivers that also have posed slope stability problems (Fig. 1). The volume of lignite extraction ranges from 7.5-10 million tones annually. The mine expected to end exploitation in 2044, but probably it will be earlier.

To provide reliable detection of landslide movements in and gain a better understanding of triggers, the application of complementary research methods is of particular importance (Demirell 2011). The observational methods may be used to check the size of the displacements. It should be noted that some types of methods only allow for the measurement of surface movements, while others allow for in-place ground displacements (Lu and Weng 2007). For earth flow landslides (Cruden and Varnes 1996), not all of the monitoring methods could be used due to the size of the observed displacements. Inclinometers could be damaged. The selection of instrumentation depends on observed movements, groundwater conditions, pore pressures, and stresses. Online measurement of small, superficial displacements, pore pressures and numerical modeling could help provide the precursor's data to predict catastrophic failure (Wilkins et al. 2003). The first part of the paper presents and discusses the largest landslides that have occurred in Polish opencast mines and the remediation methods that were implemented. The second part is dedicated to the use of modern monitoring techniques in Polish mines, as well as data collection and processing. The paper presents results of the EURFCS project.

2 LANDSLIDES IN THE TUROW MINE

The second-largest Polish opencast lignite mine near Bogatynia is characterized by complex geological conditions It is in specific location between two rivers in the vicinity of state borders with Germany and the Czech Republic (Fig. 1). The mine, located in the Zytawski Basin tectonic rift built from Paleozoic rocks and filled by Neogene deposits, is one of the most tectonically disturbed in Poland (Fig. 2).

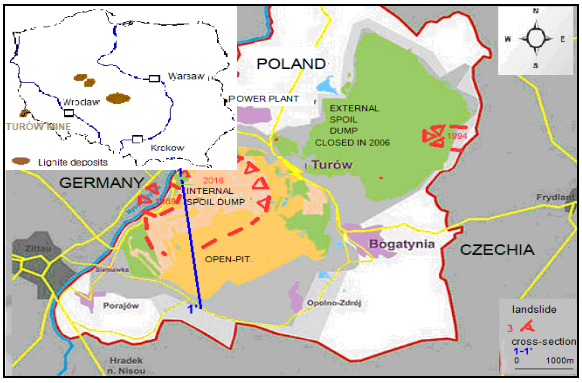


Figure 1. Location of the Turow Mine and the largest landslides.

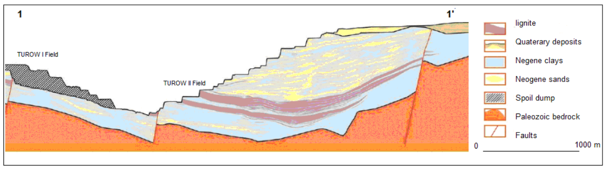


Figure 2. Geological cross-section 1-1' Turów Mine, locat on Fig. 1

Three dominant NW-SE,W-E, and SW-NE directions of dislocations formed the tectonic ditches and the main structural elements. Most are associated with two faults, the main fault and the southern fault. The near-surface parts of the deposit are glacitectonically disturbed and occur in the form of folds disappearing with the depth. Most of landslides in this mine was related to open-pit, external, and internal spoil dump slopes. In the pit, movements were often connected with faults and structural surfaces inclined consistently in the direction of the slope inclination built of predominantly clayey soils with low strength parameters. Other important triggers include a steep slope and layer inclination, high heights of operating levels, the long life of the slopes, and stress relaxation caused by lignite exploitation, cracks, leaks of groundwater, failures of deep drainage systems, and intense rainfall. The occurrence of the thickest lignite deposits near the protective pillar of the Nysa Luzycka River and the storage of extremely high masses of overburden in the outer spoil heap until 2006 and currently in the inner spoil heap caused several very serious slope stability problems. The most dangerous landslide hazard in this mine occurred in 1989 on the pillar of the Nysa Luzycka River (Fig. 1). It posed a threat to the state border with Germany and risked dislocation at the protective pillar and mine flooding. The presence of two rivers close to the open pit, the Nysa Luzycka (near the western boundary) and the Miedzianka (near the eastern boundary), pose the risk of water seepage into the mine. The specific location of the Turow deposit between two rivers is conducive to the emergence of threats, which threatens infiltration through fault gaps, especially at high water levels in these rivers or the entry of their waters into the open pit. The loss of stability may be caused by insufficient drainage of the internal dump base and the probable occurrence of significant changes in pore pressures in the soil of the internal dump, which triggered the displacements. This was reflected in the flooding of the two lower mine floors in 2010..The first threat to the stability of the permanent slopes of the Turow Mine occurred in 1989. The movements occured near the Nysa Luzycka River on the border with Germany. Exploitation carried out at the zone with the largest volume of brown coal near the protective pillar of the river at the turn of 1989 and 1990 caused a threat to the stability of the entire western slope of the mine. The pillar's protective zone in 1990 was 160-240 m wide, 100 m deep, and had a general slope inclination of 19 degrees. Exploitation carried out in 1988 at a depth of 100 m below the first lignite seam in the deepest part of the mine led to the activation of displacements (Milkowski 2009). The appearance of the first cracks in the zone of the protective pillar was detected in 1989. At that time, the level of the bottom of the open pit in its western part was uplifted and the road to the border crossing with Germany was cracked. The direct cause of the threat was lignite exploitation at a pillar level of +124/140 m a.s.l. that changed the state of stresses in the rock mass. These were caused by mining carried out too close to the pillar zone with the largest thickness of lignite. The activation triggers of other movements were a consistent inclination of layers, the occurrence of clays and low strength weathered rocks, groundwater infiltration and seepage, slope geometry, and the long life of the slope. The movements of 40-50 mm per month were measured in inclinometers at depths of 53-70 m. The plan for the stabilization of the pillar zone included the construction of buttress support and a 560 m-long bedrock drainage system. Calculations of slope stability, taking into account the support of the buttress, showed values of Fos=1.2-1.3, guaranteeing the stability of the slope. The buttress was formed in two stages: the initial 144,000 m^3, and the second 3.5 million m^3, by the end of June 1990. After stabilizing the risk zone, the mine implemented a special geotechnical and hydrogeological monitoring system. In 2010, this allowed lignite to be exploited at a depth of 100-200 m below the natural terrain level. This was also possible due to the reduction of slope angle to 10-12 degrees (Milkowski 2009). Landslides on the external spoil dump of this mine have been recorded since the beginning of its existence in the 1960s. They were particularly noticeable in the 1990s due to the huge volume of the spoil dumpsite, amounting to 1.7 billion m^3. Its height of 245 m caused numerous problems with the stability of the slopes. The Swiniec landslide, which occurred in December 1994, had a volume of 6 million m^3. The landslide was over 1300 m long, 750 m wide, and covered an area of 68 ha (Fig. 3).


Figure 3. Turow Mine external spoil dump landslide, Dec. 1994.

At that time, the eastern part of the spoil heap was located about 150-300 m from the border with the Czech Republic. The landslide was caused by the storage of large masses of overburden in difficult geotechnical conditions. Soil dump masses covered the former river spring area and had an inefficient drainage system built at the beginning of the 1960s. The bedrock substrate layers represent low strength loess and clayey soils. The direct cause of the displacement activation was a significant increase in the height of the spoil heap from 370 to 415 m a.s.l. in the southeastern part of the spoil dump. Very high and steep slopes, reaching in some cases up to 70 m, were formed there at that time. An additional factor was low strength parameters of clayey soils transported by belt conveyors over a distance of more than 15 kilometers, which resulted in its strength parameters detoriation and partial liquefaction. One of the additional failure triggers was caused by the failure of one of the dumping machines. This resulted in the loading of the endangered area by another dumping machine, temporarily directing double the overburden masses that were originally planned to that area. After that, the first displacements of 0.5 m were observed on December 7, 1994 at a level of +415 m a.s.l. On the following days, the displacements increased to 25 m per day. The total displacements reached 170 m in the upper part of the landslide and 92 m on its head. The observed movements ranged from 5 to 22 m per day until December 13, 1994. The landslide tongue moved towards the border with the Czech Republic at a distance of 70 m between December 10 and December 12, 1994. The reclamation included drainage and rescue stabilization works. However, due to the size of the landslide masses, the possibilities of stabilization were limited. The retaining wall, which was 343 m long and built of Larssen steel elements, was driven into the ground to a depth of 5.5-14 m. Three boreholes were drilled to allow for the drainage of groundwater from the contact layers of the landslide bed. The pumps operated 24 hours a day. The newly built retaining wall was partially destroyed on December 22, 1994. Ten special load-bearing structures made of reinforced concrete were built to strengthen it. This work was successful, and on January 2, 1995 the movements disappeared. Stabilization work included the reclamation of the landslide colluviums, soil replacement, surface drainage, and the forestation of 17 km^2. In subsequent years, a new monitoring system was built including inclinometers, piezometers, pore pressure gauges, and ground laser scanning. These measurements were supplemented with CPTU soundings (Janecki and Bednarczyk 1998). During the CPTU tests conducted by the author using the Hysson 200 penetrometer at the spoil dump area, undisturbed soil sampling was performed. This research delivered samples for laboratory index, compressibility, and strength testing (Borecka 2007). After closing of external spoil dump in 2006 landslides in also occurred several times on the formed internal spoil dump. They became more visible as the volume of stored masses increased. These threats became evident on September 27, 2016 in the form of a extremely dangerous landslide (Fig. 4).

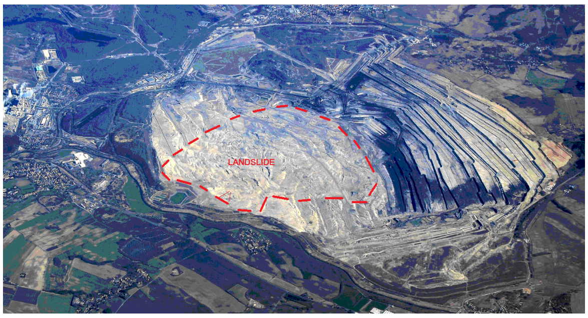


Figure 4. The Turow Mine, landslide of internal spoil dump, 2016.

The ground movements occurred in the NNW-SSE direction and covered nearly the entire open pit to the opposite side of the mine. The landslide had an area of 2.5 x 2.8 km^2 and a volume of approximately 0.8-1billion m^3. The landslide covered all the dumping levels from the surface of the terrain to the bottom of the opencast pit at a depth of about 200 m and destroyed a significant part of the overburden transportation system, including one dumping machine. The covering of the lowest part of the open pit and part of the lignite deposit by spoil dumps required costly reclamation and stabilization work to enable further exploitation. The most probable cause of this landslide, which included very large spoil dump masses, seems to be that the slopes were too high, their inclination was too steep, and the drainage of the bedrock layers was ineffective. Another trigger was the low strength parameters of the dumped clayey soils and the possible infiltration of water from the pillar of the Nysa River.

3 LANDSLIDES IN THE BELCHATOW MINE

The largest Polish opencast mine in Belchatow is located in tectonic rift, formed in Mesozoic limestones and marls and filled by Neogene deposits. Mesozoic blocks are separated along faults and dislocations with developed karst processes. The mine leads the exploitation on two operational fields Belchatow and Szczercow, separated by a salt dome (Figs. 5,6). The thickness of Neogene sediments within the rift is about 150-310 m, about 5-15 times greater than outside the rift. The thickness of the main lignite seam varies between 20-60 m. The western border of the Belchatow Field, where the in-situ remote monitoring system has been installed, is located near the Debina salt dome in the tectonic zone with many faults. This influence affects the state of stresses in the rock mass. Exploitation at a depth of over 300 m and low parameters of clayey soils occurring on the slopes often activates landslides. Most of the landslides on the western slope have occurred on structural surfaces above and within the main lignite seam bed. On the southern slope, landslides have occurred near the deep tectonic structure of the "second-order ditch" with the highest thickness of brown coal. Based on previous field and monitoring observations, it was found that the displacement occurred on the ceiling of the lignite complex towards the excavation. There were also ground movements in the lignite seam towards the excavation. Over 85% of the landslides caused by mining exploitation have been structural. Landslides have often occurred at the northern and southern slopes of this mine, inclined 1:4, where there is contact between the lignite roof and clays. The landslide volumes have varied between several thousand and 3.5 million m^3, and the speed of displacement has ranged from 2 mm to even 1 m/day.

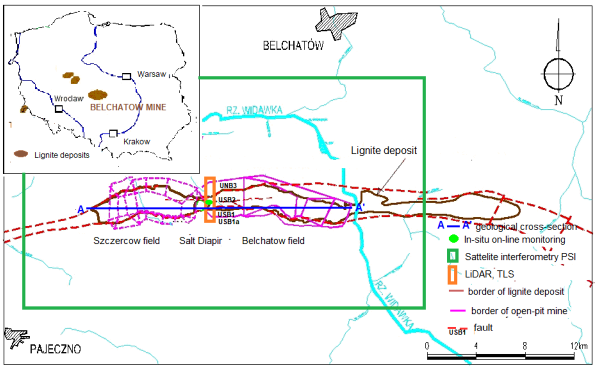


Figure 5. Location of the investigations , Bełchatów Mine

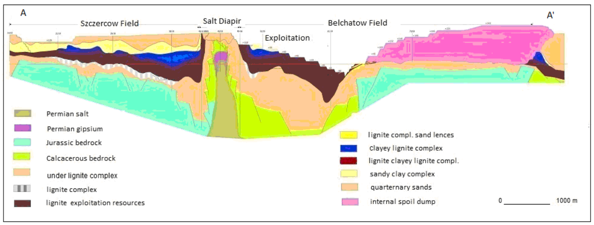


Figure 6. Geological cross-sect. A-A' Bełchatow Mine, loc. on Fig.5

Mass movements on this slope have been observed practically throughout the entire exploitation. Other serious threats have occurred on the northern slope where conveyor belt transport lines were located in low strength varved clays. The most unstable conditions occurred when they were inclined towards the open pit and when their ceiling was wet. Low strength, cracked clayey soils are associated with tectonic deformations, faults, and zones with large changes in layer thickness due to differential settlement and compaction. These soils significantly reduce the stability of the slopes. Another important factor determining the development of landslides are groundwater effluents on sandy lens slopes and areas of permeable and impermeable soil stratification, as well as those related to rainfall and solifluction processes. In the western part of the Belchatow Field, where the Slopes Project research was carried out, geotechnical engineering conditions were also influenced by tectonic structures and a salt dome causing the lignite and surrounding Neogene sediments to be inclined up to 40 degrees. The Belchatow Mine has an extensive geotechnical monitoring system covering standard surveying and photogrammetric measurements, inclinometers, stress sensors, seismographs, and static soundings (Janecki et al. 1998, Bednarczyk and Sandven 2004). The most important element of this system is a network of 22 inclinometers. The measurements that have been performed since 1999. Some of the inclinometers have been damaged by shallow displacements at depths ranging from a few to about 10 meters. Standard surface methods including photogrammetry played a very important role in the conditions of large displacements. The protection of endangered areas was most often based on relieving the load on endangered slopes, reducing the angle of their inclination, or removing landslide grounds using wheel excavators. Such works were carried out in the western part of the Belchatow Field on permanent southern, northern, and western slopes. Works performed in recent years on the southern slope at the 24S landslide included relieving the load and moving the upper part of the southern slope about 60 m to the south along a length of 1400 m by collecting and removing 4 million m^3 of overburden. On the western slope, remediation included the selective exploitation of thin lignite layers that destroyed and eliminated the slippage surfaces. Another form of protection was connected with the gradual support of the southern slope by the internal spoil dump. On the northwestern slope, it included the removal of approximately 2 million m^3 of overburden using wheel excavators. These works required costly construction of new conveyor belt lines; power supplies, pipelines, surface drainage systems and the obtainment of additional area for earthworks. Plans for the movement of wheel excavators containing important geotechnical data and monitoring measurements played a very important role in the safety procedures. For this purpose, these conditions have been regularly monitored. Determined limit values of displacement, as well as the corresponding actions concerning the protection of mining infrastructure and landslide remediation, were defined by the mine. These values were specified as the initial speed of 8-14 mm/day; warning speed of up to 20 mm/day; and critical speed of 30 mm/day (Kurpiewska et al. 2013). In 2012, 32 risk zones on slopes were detected. From the beginning of the exploitation of the Belchatow Field on the southern slope, large structural landslides were created along with the progress of exploitation in the western direction. In 2014, a large landslide was activated at the southern slope of the Belchatow Field. This slope of over 300 m is located above the “second-order ditch,” characterized by the largest volume of lignite seam. Five monitoring points in this area showed high displacements greater than 30 mm/day at the level of -35/-50 a.s.l. in January 2014 (Czarnecki et al 2015). In June 2014, movements were greater than 30 mm/day at 15 points, greater than 100 mm/day at two points, and greater than 200 mm/day at one point. These predictions were confirmed by the movements observed from May 2015 to February 2018, which were significant and amounted to 573-884 mm/day (Cala et al. 2019). Total displacements on the landslide amounted to 61-134 m, with a maximum uplift of the slope of 45 m. These large-scale processes also led to the uplift of brown coal at the bottom of the mine to the height of several meters. Thanks to many years of practice, changes in the slope inclination, partial support of the slope by the internal dump, and the cessation of coal mining in the deeper layers, displacements were reduced.

Figure 7. The on-line monitoring station in Belchatow mine.

4 MONITORING MEASUREMENTS

In-situ nearly real-time landslide monitoring methods were implemented in the Belchatow Mine. The monitoring point was located on the western slope of the Belchatow Field at the level of +42 a.s.l. (Figs. 5,6). In December 2016, the first on-line landslide monitoring was installed in the Polish open-pit mine.A similar system, the first on-line monitoring system for landslides in Poland, was installed earlier in 2010 by the author in the Carpathian Mts. (Bednarczyk 2018). The system in the Belchatow Mine is 100 m deep and enables continuous observation of the existing displacements and pore pressure in real time. The other remote monitoring methods tested in this mine included TLS ground-based laser scanning, LiDAR UAV, and PSI.

5 FIELD WORKS AND LABORATORY TESTS

The borehole was located in the northern part of the western slope of the Belchatow Field. Field works included the description of the boreholes, sampling, and installation of an on-line monitoring system. Core impregnated drillings of 132 mm recognized the soil profile to a depth of 100 m (below the level of +42 m a.s.l.) and delivered 31 undisturbed soil samples. The grain size analysis showed that soils represented sandy clays, loams, and clayey sands. The highest natural moisture content was recognized in clayey sands at 32.8%, with the lowest at 13.6-16.3%. The content of organic matter amounted to 3-19.3%. Volumetric density ranged from 1.64 g/cm^3 for sandy clay to 2.29 g/cm^3 for loamy sand. The degree of plasticity was 0.17 for clayey sand and the highest value was 0.41 for sandy clay. Direct shear tests showed for sandy clays the cohesion values of 19.5 kPa and the angle of friction of 22.8 degrees. Compressibility tests detected modules of primary and secondary consolidation amounting to Mo = 1.74 MPa and M = 8.4 MPa, respectively. The CIU and CID triaxial tests of 30 soil samples (11 tests) were performed with preliminary consolidation and saturation of samples and control of B parameter (Tab. 1).

Tab. 1 Results of the triaxial tests.

No	Soil type	Depth [m]	Met.	Strength parameters			
				Friction angle		Cohesion	
				φ[°]	φ’[°]	c [kPa]	c’[kPa]
1	Sandy loam	4.0	CIU	42.8	42.9	0.00	0.00
2	Sandy silt	16.0	CIU	33.5	34.1	27.7	19.7
3	Loam	29.0	CIU	11.3	14.5	66.2	103.2
4	Silty clay	33.0	CIU	21.8	30.3	129.1	32.5
5	Lignite	33.5	CID	-	19.0	-	200.0
6	Clay	46.0	CIU	8.54	9.8	6.31	18.7
7	Loamy sand	46.5	CIU	55.1	28.6	0.00	0.00
8	Clay	50.0	CIU	12.9	15.5	373.0	345.1
9	Loamy sand	57.0	CIU	29.1	28.4	0.00	0.00
10	Silty sand	81.0	CIU	35.3	34.9	32.3	41.2
11	Silty sand	81.5	CID	32.3	32.4	154.8	153.6

Samples of the same soils were sheared at increasing pressures in the chamber of the triaxial apparatus. The Coulomb-Mohr criterion was used for the interpretation of the results. The tests showed very variable values of strength parameters. The lowest parameters were observed in cohesive soils such as silty soils and clays. The lowest effective values of the friction angle and consistency, φ'=9.8° and c'=17.7 kPa, were found in clays below the main coal bed at a depth of 46 m, near the slip surface (Tab.1).

6 ON-LINE MONITORING SYSTEM

The in-situ remote monitoring system was 100 m deep. The depth of the installation allows for recording movements from +42 m to -58 m a.s.l (Fig. 8). The system has special rigid measuring segments with a length of 0.5 m connected by movable joints. They can move in any direction but are protected against twisting. The instrumentation consists of 200 displacement sensors, three magnetometers, and a pore pressure transducer in the ground at a depth of 30 m. Each segment contains three sensors within the range of 45 degrees and an accuracy of 0.02 mm/m. The ground temperature sensor is located in every fourth segment. The datalogger and the GPRS data transmission system powered by a solar panel enable on-line access to the data. Measurements were taken every 6 hour from Dec. 19, 2016 to Feb. 21, 2021. On-line monitoring data collected from December 20, 2016 until the end of October 2019 showed that the largest cumulated displacements in the slope inclination x-direction reached 258 mm. In the perpendicular y-direction, they reached 60 mm. The largest displacements occurred at a depth of 44 m (Fig. 8).

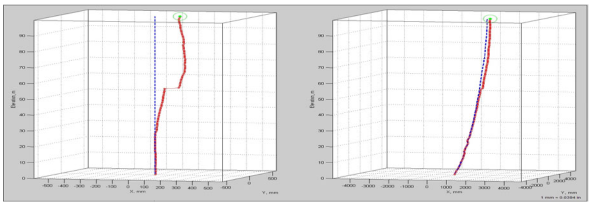


Figure 8. Cumulative displacements Belchatow (X,Y), 3D model.

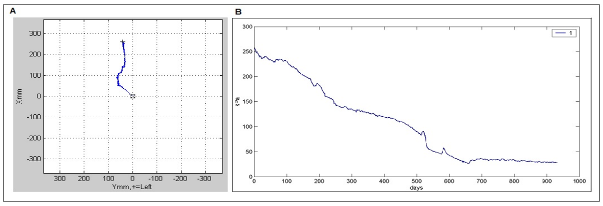


Figure 9. Displacement direction (A) pore pressure (B).

The total magnitude of displacement was 290 mm. The highest displacements of 80 mm were observed in June-July 2018. High displacements were also observed in February 2017 at 60 mm; in August-September 2017 at 35 mm; and in February-May 2019, when they increased by 60 mm. The rotation of the system was corrected using three magnetometers. These measurements indicated that rotation was the highest at 44 m, near the shearing zone where it reached up to 50 degrees. The initial pore pressure of 258 kPa at 30 m decreased to 25 kPa after a period of three years (Fig. 9). The significant drop in the pore pressure was probably due to the lignite mining and the mine dewatering system. Movements in the deeper bedrock layers were caused by changes in stresses in the rock mass and the start of the storage of spoil dump soils in the higher parts of the western slope. It was also influenced by the stresses from the salt dome deposit.

7 SATELLITE, LIDAR, UAV AND TLS MONITORING

PSI satellite radar scanning in high resolution, TLS, and drone-based LiDAR have been practically tested in the Slopes Project at the Belchatow Field. High-resolution radar scanning from CosmoSkyMed satellites (with an accuracy of 5-10 mm) was performed by GAP (Technical University of Bari, Italy). In total, from 2016 to 2018, 50 high-resolution radar images were made in a square of 40 x 40 km. Based on the photographs taken, 781,206 points were identified for which displacement values were determined. In total, 14 zones with increased displacements were identified on the external overburden dump in Szczercow and several other regions covering the slopes of the Belchatow and Szczercow opencast pits. The highest subsidence of up to 60 mm/year was found on the eastern slope of the external spoil dump (Fig. 10). On the western slope of this dump, the settlement was 30-40 mm/year. In the area of the southern slope, the detected displacements were 19-24 mm/year. However, the data for the southern slope are not representative because of the high range of displacements occurring on this slope. In the area of the investigated western slope surface, displacement varied from 9.5 to 10 mm/year. These measurements enabled a very detailed analysis of displacements in a large area. It should be noted, however, that the method allows for examining displacements initiating larger landslides. However, it also has limitations related to places where the morphology changes very quickly and does not allow for a comparison of the same elements of the terrain. This is the case in places where the displacements and changes of land surface are very large and may amount to up to 1000 mm/day for newly stored soils. Airborne scanning were used by Ineris (France) to build a numerical terrain model on the western slope of the Belchatow Mine. LiDAR UAV measurements using YellowScan scanners. The results of LiDAR scanning from a drone and aerial photographs between November 2016 and March 2017 indicate the occurrence of displacements and discontinuities shown from green to red, with corresponding displacement values estimated at approximately 6 mm. They identify several displacement areas, including area near the in-situ monitoring at the level of +42 m a.s.l. Other measurements performed as part of the project included TLS scanning of the western slope carried out in June 2016 by the Mining Department of Exeter University (UK) using the Rigel-VZ4000 laser from four locations on the southern slope of the Belchatow Field and two on the northern slope create a numerical terrain model. The results of these analyses indicate that the angles of inclination of individual slopes range from several to about 70 degrees (Fig. 11). To identify four landslide zones, the results of TLS were compared with the results of the later LiDAR UAV scan of Nov. 2016 and aerial photogrammetry of Mar. 2017 (Fig. 12).

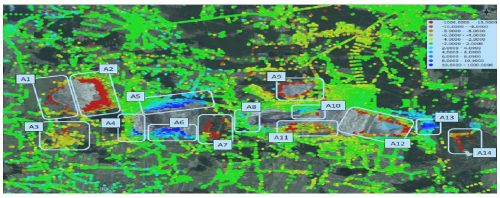


Figure 10. PSI satellite int results (Marshall 2019), location on Fig. 4

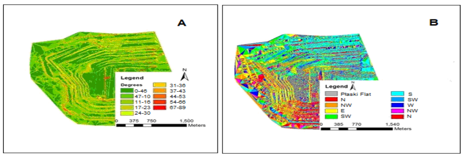


Figure 11. Angle of inclination (A) and direction of inclination (B) based on TLS laser scanning, (Marshall 2019), location on Fig. 4

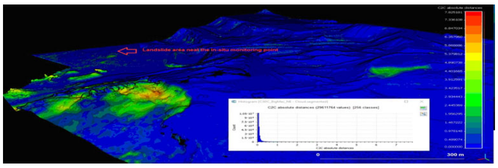


Figure 12. Comparison of LiDAR UAV measurements with aerial photogrammetry (Marshall 2019) location on Fig. 4

8 SLOPE STABILITY ANALYSES

Due to the complex geological structure, the slope stability analyses required a generalization of the introduced model. For this purpose, nine layers with similar strength parameters were selected. The strength parameters used for calculations were taken from the performed laboratory tests and corrected values from previous tests and modeling. The correction method for effective calculation parameters was estimated using previous assessments (Hawrysz 2013, Marinos and Hook 2005). Slope stability was analyzed using 2D Flac 7.0 in two cross-sections, 18WE and 20WE, with the highest slope inclination (Fig. 13).

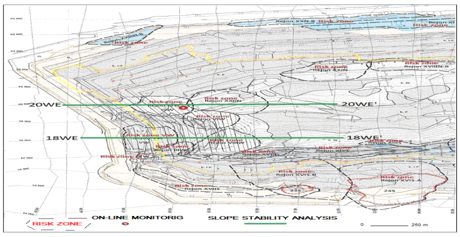
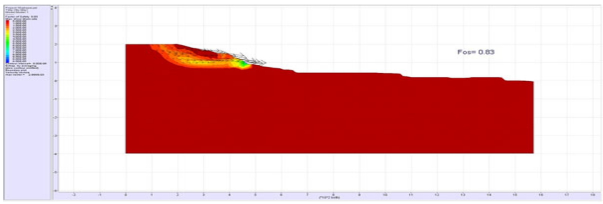


Figure 13. Localization of slope stability analyses Belchatow Mine.



Numerical modeling 18WE, Flac 8.0 20 WE, Fos=0.83.

The calculation included grid 1×1 m and 50,000 calculation steps. The applied linear-elastic constitutive model contained an approximate depth of the groundwater table. The modeling results indicate a high risk for a landslide on the western slope. The values of the Fos were low and ranged from 0.83 in section 18 WE near a landslide (Fig. 14) to 1.14 in section 20 WE. Analyses were also performed using the LEM method using the Bishop and the Janbu approaches. The results of analyses are presented in Tab. 2. The results of Flac analyses indicate a low degree of stability for the examined slope, which is confirmed by the results of in situ, LiDAR and PSI Satellite monitoring (Fig. 10 and 12), measurements, and field observations. LEM methods with the same strength parameters indicate significantly higher values of stability coefficients Fos=1.34-1.46 for the 18WE cross-section and 1.16-1.27 for 20WE. SSR method more precisely locates the place of the slide, better reflecting the actual conditions, which was confirmed by the results of monitoring and field observations

Table 2. Results of slope stability analisis, Belchatow Mine.

Method	Fos	Remarks
Flac (SSR)	1,14(18WE) 0.83 (20WE)	18 WE displacements in middle part of the slope 20WE displacements in upper part of the slope
LEM (Bishop)	1.16 (18WE) 1.34 (20WE)	18 WE small displacements . in middle part of the slope 20 WE displacements in whole slope

9 CONLUSSIONS

The examples of the most dangerous landslides in the largest Polish opencast mines were presented. Serious economic and environmental consequences of landslides necessitating their forecasting and prevention. Selected monitoring methods must depend on the rate and type of displacements, and required accuracy. When the exploitation is undertaken in the vicinity of protective pillars, national borders, important infrastructure, or the storage of very large overburden masses, the geotechnical engineering conditions should be analyzed very carefully. It is recommended to consult experts representing research centers and universities regarding the projects. The design of slopes should be economical, but also safe. The exemplar investigations at the Belchatow Mine, enabled the analysis of local conditions. The displacements on the W slope of the Belchatow Field were caused by the impact of mining operations and by stresses from the salt dome. The remote monitoring system, which is the first of its kind in a Polish open-pit mine, provided new data. It detected movements of 280 mm with the accompanying drop in pore pressure by 230 kPa. The slope was characterized by a low Fos=0.83-1.10. In other regions of the mine, PSI scanning allowed for the separation of 14 zones of increased displacements. The TLS and Lidar UAV scanning on W-slope detected 4 displacement zones. However, surface displacements (10-24 mm/year) were significantly smaller there that in-situ (≈ 90mm /year at 44 m depth). The project results indicated that every monitoring method had benefits and disadvantages. It is very important to calibrate the scanning results with in-situ monitoring and laboratory test data. Full elimination of landslide hazards in opencast lignite mines is not possible. Knowledge of the geological processes that existed in the past, their scale, as well as the latest research, should contribute to better identification of risk and selection of optimal remediation. The cost of monitoring and expert opinions seems to be quite high initially; however, it is insignificant considering the cost of rescue and stabilization work. Geotechnical engineering management could provide mining authorities with a valuable tool for the recognition and lowering the risk.

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