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PRACTICAL USE OF MODERN INVESTIGATION AND MONITORING METHODS IN POLISH LANDSLIDE REMEDIATION PROJECTS

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Abstract. This paper discusses exemplary landslide investigations in natural Carpathian and man-made opencast mine slopes. Research methods included mapping, core drilling, laboratory testing, GPR scanning, on-line inclinometer, piezometer, and pore pressure monitoring and also numerical modelling. Landslide triggers were complex and diverse. On flysch slopes movements were activated by heavy rainfalls and in opencast mines, by exploiting the parameters of clayey soils. Precise prediction of landslide activation is impossible. Identification of landslide triggers for mitigation measures requires a multiple analysis of integrated external and internal variables.

Keywords: Lanslide, mine slopes, landslide triggers.

1. Introduction

Ground movements cause considerable economic loss in many countries every year. Most of the landslides in Poland, approximately 95 % occurred on natural slopes in the Carpathian Mountains [1]. Other, large man-induced mass movements are also observed in Polish lignite opencast mines. Warning of landslide hazard in Poland is mostly based on field inspection and mapping. These works could recognize landslide location and basic geometrical parameters as size and approximate depth. However, more advanced landslide monitoring and early warning studies requires identification of many external and internal activation factors and precise location of sliding surface depth using advanced investigation and monitoring methods. Observed in the Polish Carpathians mass movement constitutes the debris slide type of landslide [2]. Identifying activation of flysch soil-rock type colluviums is very complicated. It requires usage of expensive core impregnated drillings, geophysics, laboratory tests and complex monitoring methods. Precise detection of sliding surfaces locations, movements ranges and directions is basic for recognition of remediation possibilities. It is possible to detect surface displacement using many types of modern monitoring systems. Besides the standard geodesy comprehensive data could be delivered also by GPS, implementation of satellite remote sensing or TLS terrestrial laser scanning. In-situ extensometers and inclinometers could precisely measure ground displacements. Groundwater conditions could be studied using piezometers and pore pressure transducers. Surface displacement warning systems cover large areas and allow precise monitoring. Earlier and more precise detection of ground displacements is possible using in-depth monitoring. Different parameters can be monitored to provide meteorological, ground displacement, groundwater and pore pressure data [3]. Prediction of landslide activation time could be based the analysis of the movements and rainfall or groundwater conditions [4, 5]. Measurements of these parameters and its interpretation could be used to define warning triggers for early warning. The paper presents selected examples of landslide investigations in which the author had the opportunity to participate. Investigations in the Polish Carpathians and conventional monitoring measurements date from 2005. The first attempt using in-situ remote monitoring for landslide monitoring in Poland was made in 2010. The second in-situ remote system was installed in Belchatow opencast mine in 2016. However much new technologies can deliver significant data, very important is the proper interpretation of geotechnical engineering conditions. Instrumentation methods always need careful design and calibration.

2. Landslide Investigations in the Polish Carpathians

The author of this paper had the opportunity to investigate 25 landslides and participate in the design of 7 landslide road reconstructions in SE Poland [6, 7]. Landslides occurred on mountain slopes in Neogene flysch layers built from claystones and sandstones with a shallow groundwater level depth. Creep type ground movements have a depth of 5–16 m and a speed of a few millimetres to several centimetres a year. The proposed research methods were included in the design of stabilization projects or the preliminary counteraction concepts (Figure 1). On two roads, due to the high cost of stabilization, only temporary repairs were performed. In one case, slope investigation was conducted for the design infrastructure at a landslide-prone slope for the Polish Oil & Gas Company [8]. One project was realized for protection of the cultural heritage of the Saint John Chapel in Dukla [9]. The main purpose of the research was to define the possibilities and the methods of landslide remedial work.

2.1. Site investigation

The site investigation program was dependent on the risk posed by every landslide, the volume of unstable mass and observed displacements. It included preparation of geological engineering reports (Figure 2) in risk areas (2005–2008). Research methods included high-quality boreholes, undisturbed sampling, GPS-RTK mapping (Figure 3) and GPR near-surface geophysical scanning (Figure 4). Conventional instrumentation was applied in site investigations boreholes (2005–2014). On-line systems were installed in specially drilled boreholes (2010). An updated version of the actual landslide terrain morphology was very important due to the lack of current landslide maps and significant morphological changes caused by the ground movements of recent years. In some areas, besides standard geodesy surveying GPS-RTK measurements were implemented given their efficiency and low cost in relation to conventional mapping. The GPS post-processing measurements were found to be an effective way of landslide mapping. They had the horizontal and vertical accuracy of 1 cm. However, some difficulties occurred in the forests. Drilling allowed recognition of layers and inclination inside the slopes. For this reason over 800 m of drilling by the dual-core apparatus, involving a diameter of 132 mm to a depth of 9–30 m, was performed.

During these works over 200 soil samples were taken for the laboratory tests. The relatively high yield of the core (80–90 %) allowed descriptions of landslide profiles, cross-sections and in some cases recognition of the sliding surface depth. Additional data connected with slope stratification and colluviums depths were detected using 2D GPR RAMAC scanning (Figure 3). This allowed accurate measurements of changes in colluviums and the dielectric properties of bedrock layers between the boreholes. The GPR profiling was essential for construction of geotechnical cross-sections. It allowed recognition of landslide colluviums and the inclinations of layers and faults. Interpretation by the GPR method and boreholes in sandy and clayey layers proved helpful in the identification of water infiltration-prone zones. However, it is to be noted that the identification of colluviums was made possible by GPR correlation with detailed site investigation and monitoring results. With the GPR method, layer depths are only the result of interpretation and should be calibrated very carefully. The GPR method had some limitations in places such as forests or locations close to power supply lines. Interpretation of GPR landslide scanning results was not easy and should be made by experienced users of this equipment.

2.2. Instrumentation and monitoring

Nearly 500 m of inclinometer casing was installed in the Carpathians by the author. Boreholes drilled inside the site investigations were used also for inclinometer, piezometer, and pore pressure transducers. The conventional monitoring methods were used for standard inclinometer, piezometer and pore pressure monitoring before, during, and after the remediation. The network included 30 monitoring locations, which consisted of a 70 mm ABS inclinometer depth of 7–21 m and standpipe piezometers depths of 5 m. For pore pressure monitoring, pneumatic and piezoelectric transducers were located at a depth of 5–10 m. In 2010, the first on-line early warning system in Poland, involving four field stations, was installed in a landslide in Szymbark (Figure 5).

It included two on-line continuous inclinometer field stations, and an in-place inclinometer and weather station. Continuous inclinometers consisted of 3D MEMS tilt sensors every 0.5 m to a depth of 12–16 m. They included a total of 66 MEMS tilt sensors. The maximum range of measurements, up to 500 mm, is much greater compared to standard inclinometers. One segment included 3 tilt sensors, measuring a range of ±45 degrees, with an accuracy of 0.02 mm/m, an admissible error of joints of ±0.250. Every octet (8 segments) is equipped with a ground temperature sensor. The in-place inclinometer system with 3 uniaxial sensors has a length of 14 m. The GPRS data are registered every 6 hours and available online from 10 May 2010 (Figure 6 and Figure 7). The ground movement measuring devices were supplemented by three automatic pore pressure and groundwater level transducers and online weather station with measurements of rainfalls, air temperature, air pressure and air humidity. The conventional measurements were conducted every few months from 2006 until 2017, a period of over 11 years. In the first 5 years scheduled readings were taken more often, every 30–45 days, then two times a year. Automatic pore pressure readings were performed every 6 hours from 2005. Measurements allowed verification of representative values of displacements, their direction and depth. Observed ground movements varied from 50 mm to 500 mm over 12 years in time. In some cases, displacements reached critical values that made it possible to measure only the shallowest sliding surface. It was observed that the greatest displacement occurred after the highest pore pressure variations. The pore pressure rose at such a period to 60–65 kPa and then decreased to 40–45 kPa. The on-line system delivered more comprehensive data due to small 10 minutes – 6 hours reading intervals. The on-line system registered the record high rainfalls just after the installation. The reading from the weather station on June 2 reached 100 mm/m^2 in 3 hours. Total displacement reached a size of 30–60 mm to the depth of 12–15 m. The largest deformation occurred in May-June 2010 and in June-August 2011. Initial threshold values were defined as a daily displacement higher than 1 cm and rainfall higher than 100 mm a day. Two of the on-line and three of the conventional inclinometer stations were already damaged by

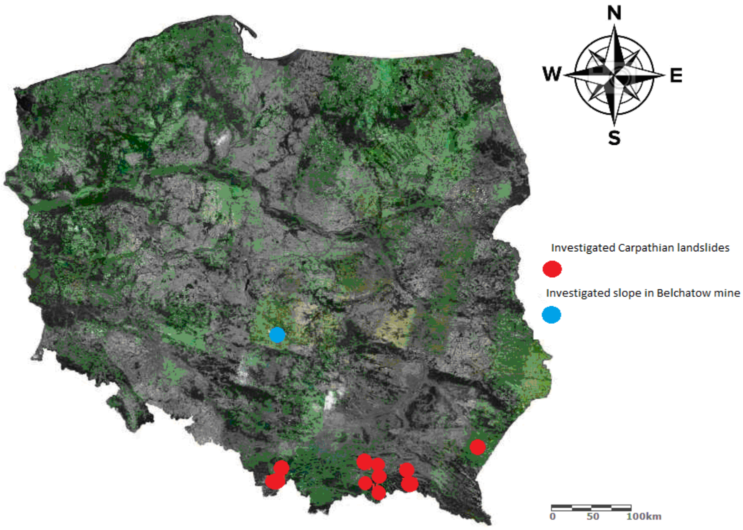

Figure 1. Localization of the investigated landslides and slopes.

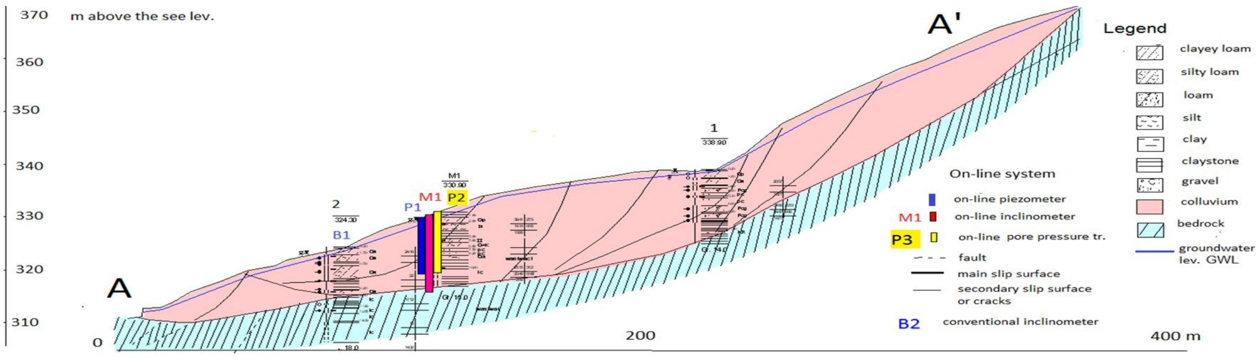

Figure 2. Geological engineering cross-section of landslide in Szymbark.

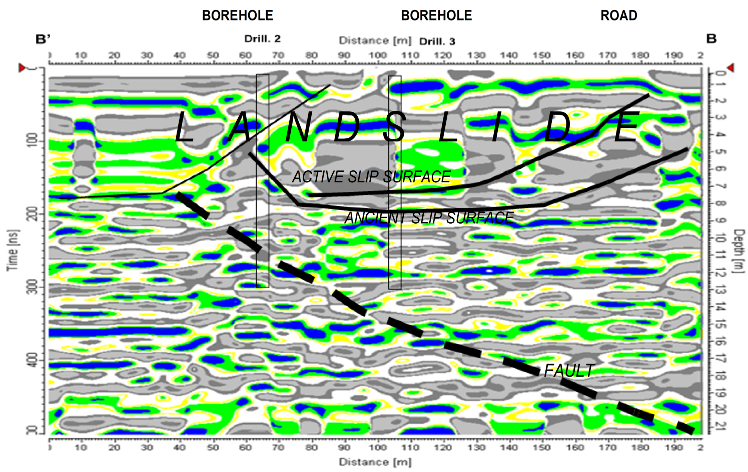

Figure 3. Sekowa landslide GPR scanning results.

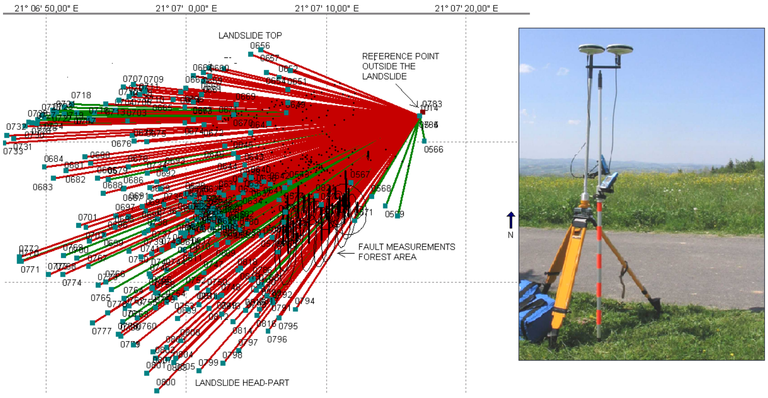

Figure 4. GPS-postprocessing results, Szymbark landslide.

Figure 5. Online landslide monitoring station, Szymbark landslide.

large displacements. The conventional and on-line measurements were conducted until the end of 2018.

2.3. Laboratory tests

To define the geotechnical parameters of colluvium, index, IL oedometer and direct shear, and CIU, CID triaxial tests were performed. The index tests included the grain size, the moisture content, the plastic and liquid limit, the bulk density, the grain-size density, and the content of organic/bituminous material. However, the preparation of samples into the oedometer and the strength test was complicated due to the occurrence of crushed rock particles in the soil samples. Therefore, the strength tests were limited to the simple direct shear tests in the shear box apparatus and only a limited number of triaxial tests. The tests detected that colluviums represented silty clays, loams, gravelly loams, claystone, and sandstone (bedrock). The investigated soil samples, had the natural moisture content of 18–37 %, varied in effective cohesion 6.5–10 kPa and an effective angle of internal friction of 11–15°. Clayey colluviums were characterized by a very high compressibility. The highest values of the moisture content and plasticity were observed in samples taken near the slip surface to depths of approximately 2–10 m, near the slip surface.

2.4. Numerical modelling

The slope stability was checked by LEM numerical modelling using the Janbu and Bishop Methods. The factor of safety FoS was calculated before and after the remediation. The strength parameters for the analysis were implemented as the lowest values from the laboratory tests and comparable experience. Limit equilibrium analyses showed that the analyzed slopes had low factors of safety FoS = 0.68–1.2. Very low values of FoS = 0.7–0.8 were calculated for the lower slope parts at landslide tongues. The FEM methods were implemented to predict the possible displacements and to compare it with the monitoring results (Figure 8). The modelling included external factors such as static or dynamic loads, shallow groundwater level and preferred slip surfaces. The modelling detected that the expected total displacement could reach without any remediation up to 33 cm.

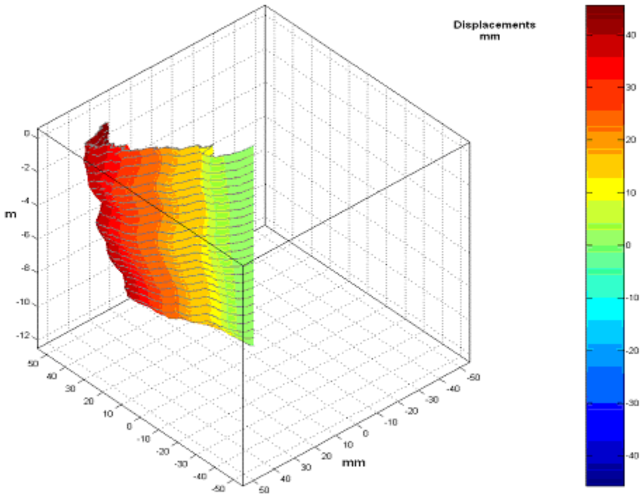

FIGURE 6. Ground displacement 3D model, Szymbark landslide.

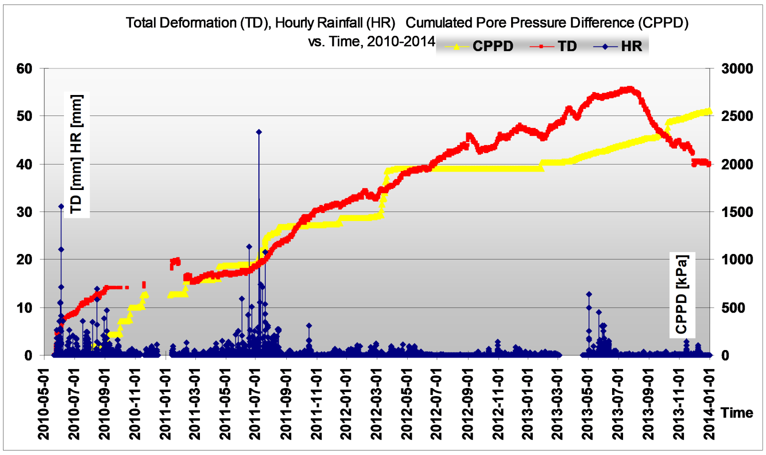

FIGURE 7. Results of on-line displacement, rainfall and pore pressure measurements, Szymabark.

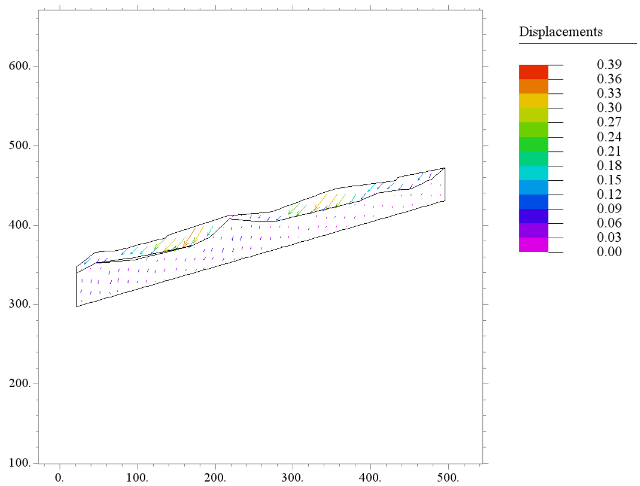

FIGURE 8. FEM numerical modelling, SoilVision software, Szymbark landslide.

3. Landslide Investigations in Polish Opencast Mines

Presented research was conducted in Belchatow mine. This opencast mine, the largest excavation in Europe, is localized in central Poland 50 km south-west from the city of Lodz. The mine is situated in the Kleszczow tectonic rift. The rift filled by Neogene deposits thickness of 15-310 m is formed in Mesozoic limestone and marl blocks, and cut by many faults (Figure 9). Neogene deposits within the rift are 5 to 15 times thicker than outside it. The thickness of the main lignite seam is 20-60 m. Exploitation in the mine is conducted on of two operational fields separated by a salt dome at Debina. The Belchatow field, located at the east, will finish the exploitation in 2020, the Szczercow field at the west in 2038. Numerous landslides in this mine were mostly structural genesis and were activated by mining activity. At Belchatow field landslides permanently occurred on the south slope of the pit and was formed on paleolandslide structural surfaces, over a deep ditch structure with the greatest thickness of lignite. Other landslide prone zone that posed risks to transportation systems and power supply lines was the north slope of this mine. This slope is built from Quaternary clays, characterized by low strength parameters. The main structural slip surfaces was formed on borders between Quaternary and Neogene deposits, and the Neogene clays with the main lignite seam. Faults cracks, glacitectonic surfaces, borders of low strength soils, varved clays were others surfaces that's allowing movements activation. Mining efficiency in this mine is affected by the complexity of the geological structure of the lignite deposit and overlay landslide-prone sediments. Registered in the mine landslides had volumes up to 3,500,000 cubic meters, with displacements from a few centimeters to nearly one meters in one day [10]. Eight landslide risk areas were identified at the west slope of Belchatow field, investigated inside the presented research.

3.1. Site investigation

Site investigations included description of core impregnated 132 mm borehole to the depth of 100 m, located at the northern part of the west slope at level of +42 m. a. s. l. The borehole was located in IVW risk area in the contact zone of the salt dome. The core obtained from the borehole were described in details. It included soil type, moisture content, consistency and field tests of the soil strength parameters. Thirty one NNS undisturbed samples (A class) for the laboratory tests were collected into stainless steel cylinders using the Osterberg sampler.

3.2. Instrumentation and monitoring

The instrumentation installed in December 2016 included an on-line continuous inclinometer system, the same type as installed in the Carpathians. However the system in Belchatow is deeper and consists of sensors, located every 0.5 m, to a depth of 100 m. The system consists from 200 ground displacement 3D measuring devices. It is built from rigid segments and includes 3 magnetometers for rotational control. Additional VW pore pressure transducer is located at a depth of 30 m. Remote monitoring data are registered every 6 hours from 19th December 2016. Till May 2018 the largest of displacements was observed in Jan-Feb 2017 during the first 40 days of measurements when they reached 70 mm. The second activation of displacements occurred in Aug-Sept 2017 when these increased another 40 mm. The largest displacements and shear strains in the direction of slope inclination (X) were recorded at the depths of 0-45 m. In the Y direction perpendicular (Y) at 27 m depth (Figure 10). Located at depth of 30 m, pore pressure sensor, registered drop of pore pressures from 258 kPa in December 2016 to 50 kPa in May 2018. This significant change of pore pressure was probably caused by coal exploitation at lower levels and mine dewatering system. However, it was observed that usually acceleration of movements usually occurred after small secondary pore pressure drops. Displacements were caused probably by the changes in stress state caused by mining and the salt dome. The initially alarm trigger was set at 30 mm per day. To the current point in the time this value has not been detected. By the end of May 2018, observed movement magnitude was 130 mm.

3.3. Laboratory test

Laboratory tests included index, direct shear, IL oedometer, triaxial CIU, CID tests. Index tests covered grain-size, moisture content, unit weight, and dry unit weight analysis. Tests included also content of organic material and Attenberg limits. Soils comprised sandy silts, sandy loams, loams and loamy sands. Moisture content was the highest in loamy sands up to 32.8 %, relatively high 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 %. The unit weight varied from 1.64 g/cm^3 for silty sand to 2.29 g/cm^3 for loamy sand. The liquidity index varied from 0.17 to 0.37 for sandy loam with the highest at 0.41 for sandy silt. Shear box tests performed detected lower values of apparent cohesion of 19.5 kPa and an apparent friction angle of 22.800 for sandy silts compared to 29 kPa and 27.900 for sandy loams. The IL oedometer test for silty sand characterized by the highest plasticity detected a constrained modulus of primary consolidation M = 1.74 MPa and a constrained modulus of secondary compression M = 8.4 MPa.

3.4. Numerical modelling

Numerical modelling was performed in two cross-sections using Flac 8.0 software (SSR Method) and LEM software (Bishop and Janbu Method). The SSR method tends to reflect the actual condition on the slopes leading to the reduction of shear strength of soil up to the stage of losing stability. The implemented

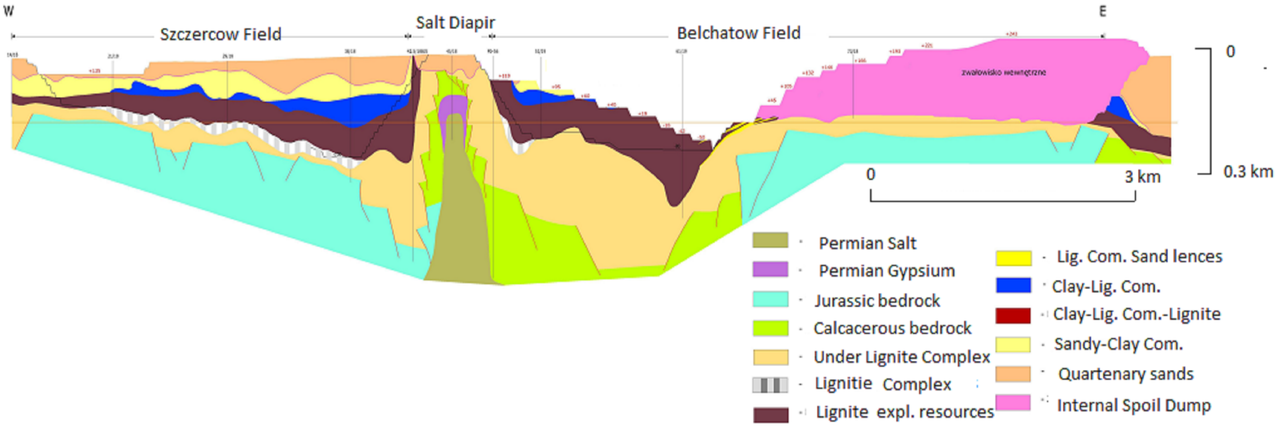

Figure 9. Geological WE cross-section of Belchatow and Szczercow Fields.

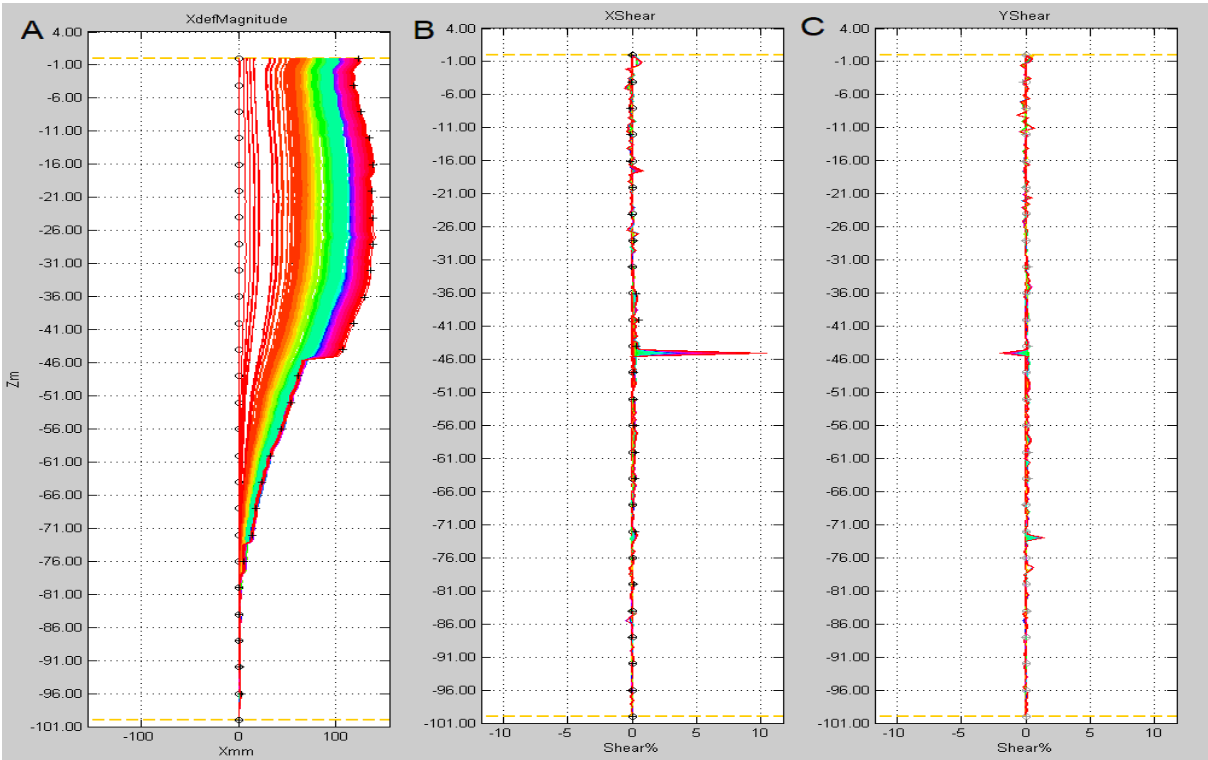

Figure 10. Magnitude of displac. (A), X shear stress (B), Y shear stress (C), Belchatow mine.

Mohr-Coulomb elasto-plastic strength model required specification of bulk density, effective cohesion and effective angle of internal friction. The obtained values of factors of safety using the SSR Method were low ranging 0.85–1.14 (Figure 11). The movements were caused by multiple factors as mining influence, the slope height, strength parameters and salt dome influence. The salt structure influence and rheological properties of salt were not included in these preliminary local analyses due to the relatively high distance to the salt dome and a lack of representative data, but it should be implemented in future analysis.

4. Summary and conclusions

The practical use of different types of geotechnical engineering investigation and monitoring technologies in exemplary projects in Poland was presented. Investigations in the Carpathians included complex geotechnical and geophysical methods that allowed recognition of landslides parameters to the depth of 15-20 m. The investigations in Belchatow opencast mine allowed recognition of layer parameters to the depth of 100 m. Presented the firsts in Poland, two on-line monitoring systems, allowed early warning of landslide risk. The on-system in Belchatow detected deep movements 235 m below the natural terrain level. This results should help the mine owner lower the risk for exploitation. Interpretation of displacements and pore pressure changes could be used as an early warning indicator. The research delivered comprehensive geotechnical data for the numerical modelling. However, investigation methods should always be cal-

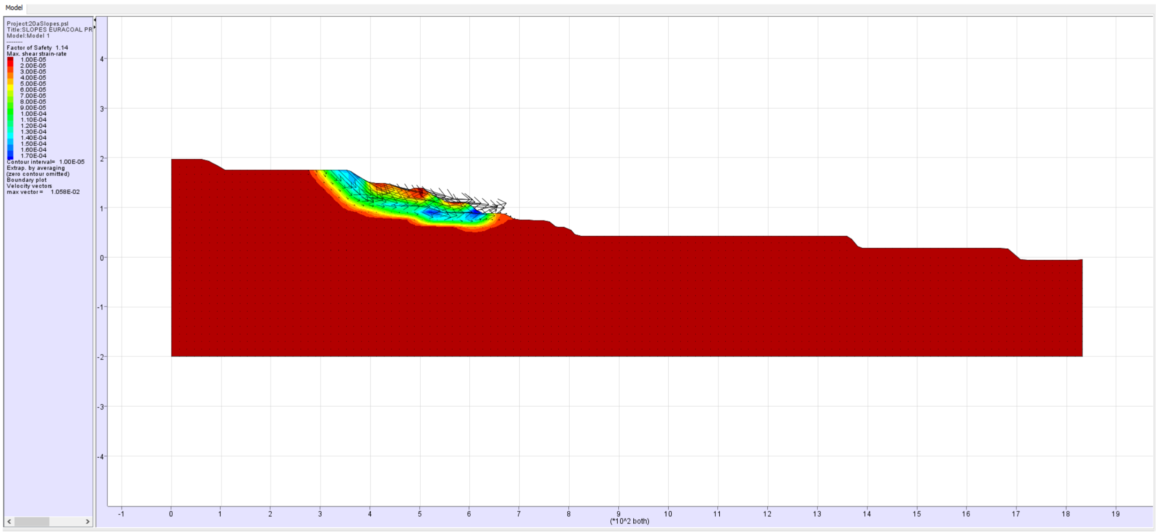

FIGURE 11. Results of SSR analysis 20WE, FoS=1.14, Belchatow mine.

ibrated for local conditions and possible threats.

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