Combined geophysical-geotechnical investigation of a landslide surface of a recultivated open-pit mine

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ABSTRACT: Properly planned and executed recultivation of open-pit mines is critical for safe re-use of the land. Erosion, surface cracks or even landslides may appear on steep slopes of not properly recultivated mine surfaces. Detailed documentation of near-surface geology and recultivation technology applied are often missing for mines closed several decades ago. Drilling or penetration tests are difficult or impossible to execute on unstable, steep slopes, therefore alternative data acquisition techniques have to be applied in addition to geotechnical measurements. Geophysical surveys can provide useful information for understanding subsurface geology and identifying critical layers/areas.
Case study of an open-pit coal mine closed in late 60ies exhibiting surface movements along an unstable slope will be presented. Slope stability calculations based on information from limited number of borehole locations and geophysical electrical tomography and seismic survey were completed and identified the critical subsurface layers.

Keywords: Recultivation; Landslide; Geotechnical; Electric tomography; Geophysical seismic survey

1. Introduction

The surveyed area is an abandoned open-pit brown coal mine in the Transdanubian Mountains, Hungary. Previously excavated shallow brown coal layer was covered by the clayey-gravel layers of the Oligocene Csatka Formation and the Szilágy clay marl of Badenian age. The surface is covered by Holocene fluvial sediments of river Séd and anthropogenic sediments postdating the mining activity. Erosion and surface movements along the artificial slopes of the mine pit are characteristic of the area. These movements are possibly related to formation boundaries and partly controlled by fault surfaces.

Mining activity lasted only for a short period of time during late 60ies. As soon as mining activity was terminated the excavated brown coal layer was covered with water in order to prevent self-ignition. The artificial lake is still present today and is used for fishing and recreational purposes. Recultivation of the slope on the NE side of the lake was not completed due to the danger of working on the steep slope. It was assumed, that natural processes will create a stable slope surface within a reasonable time. Unfortunately, this was not the case, landslides, collapses and movement of the slope continued, therefore a 30-35° slope was designed and prepared a few years ago. During this recultivation work, the surface coverage and the previously existing vegetation was removed, the surface was straightened, and the depressions were filled up with the removed material (Figure 1). These interventions, the erosion and near surface differences along layer boundaries and/or fault surfaces resulted in surface movements along the unstable slope. Surface ruptures, slides, ongoing erosion and slope movement are characteristic of the area (Figure 2). As the lake is used for recreational purposes safety and slope stability would be of primary importance.

On the site land survey was carried out periodically since 2015, therefore substantial data is available on the movement of the area.

Aim of the combined geophysical and geotechnical survey was to understand better the subsurface geology and support the engineering design for slope stability.

As a first step, core and borehole information from historical boreholes were collected, surface observations of clay layers exposed by recent erosion (Figure 3) were made. Since present slope conditions were not suitable for drilling, geotechnical surveys could only be performed at a few locations. Geophysical surveys were planned and completed in order to map the subsurface between drilling points and in areas not accessible for drilling.

Seismic profiles were measured both on land and on the lake and electrical tomography profiles were completed in both dip and strike direction on the slope northeast to the lake.

Figure 1. Surface conditions of the survey area in 2018. (Red dot indicates point of view of the photo)

Figure 2. Surface cracks and landslide on the slope NE to the lake. (Red dot indicates point of view of the photos)

Figure 3. Clay layer outcropping as a result of recent erosion. (Red dot indicates point of view of the photo)

2. Geophysical surveys performed

2.1. Electrical tomography

The purpose of the electrical surveys is to determine the subsurface resistivity distribution by making measurements on the ground surface. Electrical resistivity surveys have been used for many decades in hydrogeological, mining and geotechnical investigations.

7 geoelectrical tomography profiles were carried out with variable length (min. 82.5 m, maximum 172.5 m). 4 of them in strike (Figure 4), 3 in dip direction on the slope. The separation between the electrodes was 2.5 m for the strike direction and 1.5 m for the dip lines. The profiles were measured with Wenner-Schlumberger electrode configuration. Location of the recorded geoelectric profiles is shown by red in Figure 6.

The measured geoelectric profiles were inverted using RES2DINV software with topography taken into account during the inversion.

Figure 4. Electrical tomography profile measured in strike direction on the slope. Please note the amount of eroded sediment caused by a heavy rainfall during the measurement.

2.2. Seismic surveying

2.2.1. Land seismic survey

During land seismic surveys compressional and/or shear waves are used to image the subsurface layers. Elastic waves are generated by impulsive or vibroseis sources and the signal is sensed by one- or three-component geophones planted in the ground. The vibroseis source used for the survey was an electromechanical vibroseis source, Lightning™ manufactured by Seismic Mechatronics. This vibroseis source is a unique electromechanical vibrator capable of generating low distortion source signal in the 1-1000 Hz frequency range (Figure 5).

Since the circumstances were not ideal for application of the Lightning™ source on the terraces of the slope and at the surface cracks, both P- and S-wave recording was used only at a high-resolution seismic section running at the feet of the slope where the vibroseis source could be operated.

At the other parts of the area, only P-wave hammer source was applied and only P-wave signal was recorded.

Data recording was implemented by 3C-geophones (3 component geophones) and DMT Summit recording system.

Location of the land sesismic profiles measured are marked by dark blue colour in Figure 6.

Recorded seismic data were processed as tomography and refraction profiles. In both cases first arrivals were picked for the recorded seismic. During seismic refraction processing the picked first arrivals were used to calculate the interval velocity of the weathering layer, refractor's velocity and depth to refractor along the profile. While in seismic tomography, ray tracing is performed based on an initial velocity model. The result of the ray tracing is compared with the picked first arrival times and the differences are inverted in order to update the subsurface velocity model.

Data processing was completed using ProMAX™, SeisImager™ and Zond2DST™ software.

Figure 5. Ligthning™ seismic source in the survey area crossing a surface crack zone

2.2.2. Lake seismic survey

Water seismic acquisition is a powerful tool for imaging the subsurface geology below water covered areas. It can provide a decimetre resolution image of the subsurface layers.

A boomer sourced IKB-Seistec™ single channel seismic profiler (IKB-Technologies Ltd., Canada) was used for the survey. On the receiver side, a vertically arranged, 7-elements hydrophone group is applied to detect the seismic signals The water provides excellent coupling between the signal source, the target zone and the detectors.

During the survey, almost 6 km of seismic sections was measured (11 sections and 43 cross sections) on the lake. Survey grid is shown in light blue colour in Figure 6.

Data processing and interpretation was completed using IHS Kingdom™, Surfer™ and Isatis™ software. The interpreted horizons in time domain were converted into depth domain with a 1450 m/s acoustic wave propagation velocity characteristic for water and were referenced to the water surface of the lake.

3. Geotechnical investigations

For understanding the subsurface conditions, 3 boreholes were drilled with 25-40 m depth and continuous core sampling. Location of the boreholes is marked with red dots in Figure 6.

The core samples showed high variety of the drilled soil layer ranging from soft peat through mud to coarse gravel with underlaying strata consisting of marls and conglomerates with very different rock physical parameters. Intensive laboratory testing was completed on the core samples also confirming the high variability of the sediments building up the slopes. Complex geological conditions with various types of soil, landfill and rock strata were revealed.

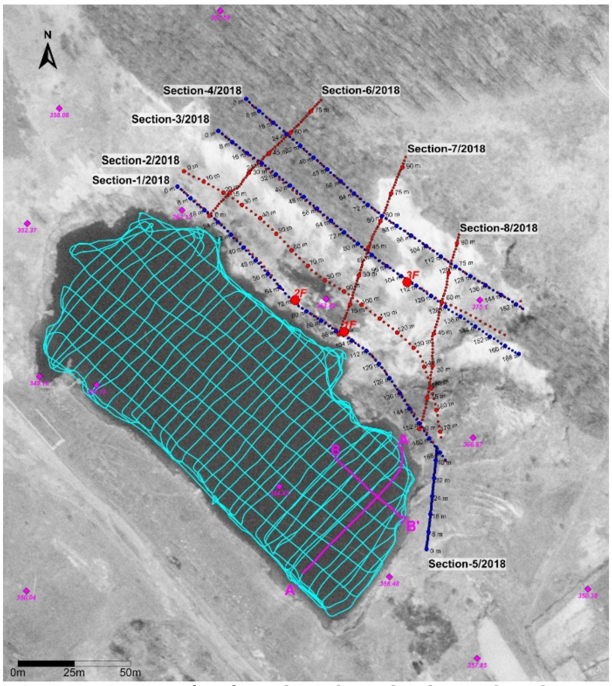

Figure 6. Location of performed geophysical and geotechnical measurements. Red colour marks location of geoelectrical profiles, dark blue land seismic, light blue water seismic profiles. Two magenta lines indicate sample profiles AA' and BB' shown in Figure 8. Red dots mark location of the geotechnical boreholes drilled, while pink colour marks the location of historical borehole locations.

4. Main results of the geophysical investigation

4.1. Lake seismic profiles

High-resolution seismic survey completed on the lake revealed the morphology of the water bottom and the layer boundaries below the lake. Mapped water bottom shown in Figure 7 indicates significant amount of material already eroded/slumped into the eastern-northeastern part of the lake. The location of this material coincides with the middle part of the slope showing strongest erosion.

Water seismic data also provided useful information on the limit of former mining activity. Coal was extracted for most of the area of the lake, however at the southeastern part of the lake coal layers were left intact and could be identified in the seismic profiles. Lake seismic profiles AA' and BB' running NE-SW and NW-SE respectively image the well layered clay-coal sequence and the eroded-slumped recent sediments covering them. Figure 8 shows the interpreted high-resolution seismic profiles measured in the southeastern part of the lake. Water bottom is the blue horizon, top of the coal-clay layers is marked by the red horizon while yellow marks the coal horizon mapped in Figure 9.

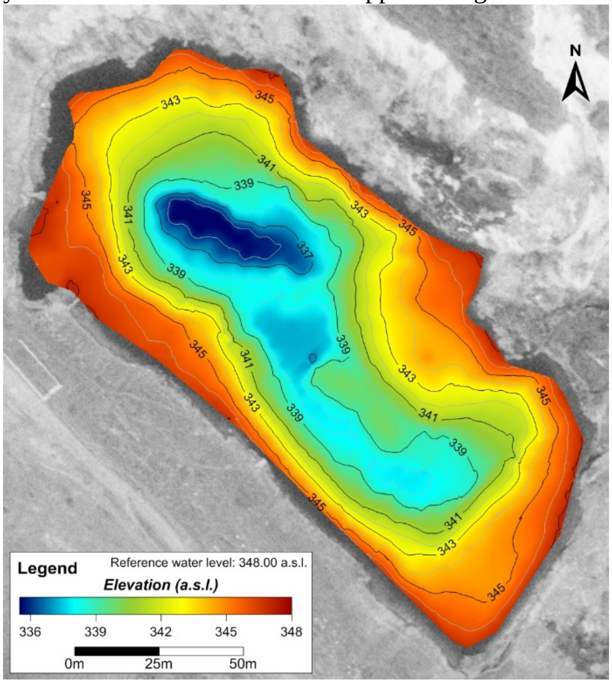

Figure 7. Water bottom morphology of the lake

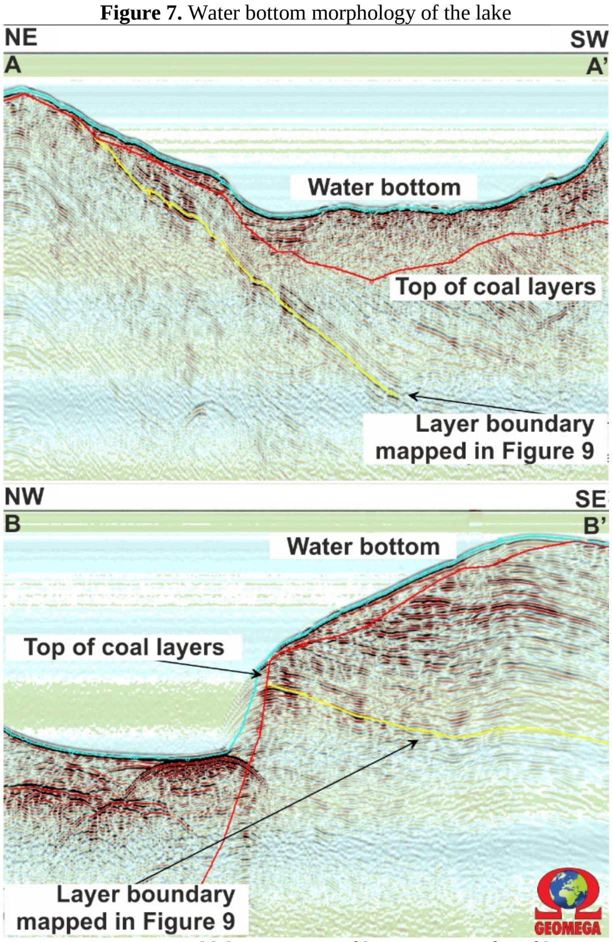

Figure 8. Interpreted lake seismic profiles. Location of profiles is shown on the maps in Figures 6 and 9.

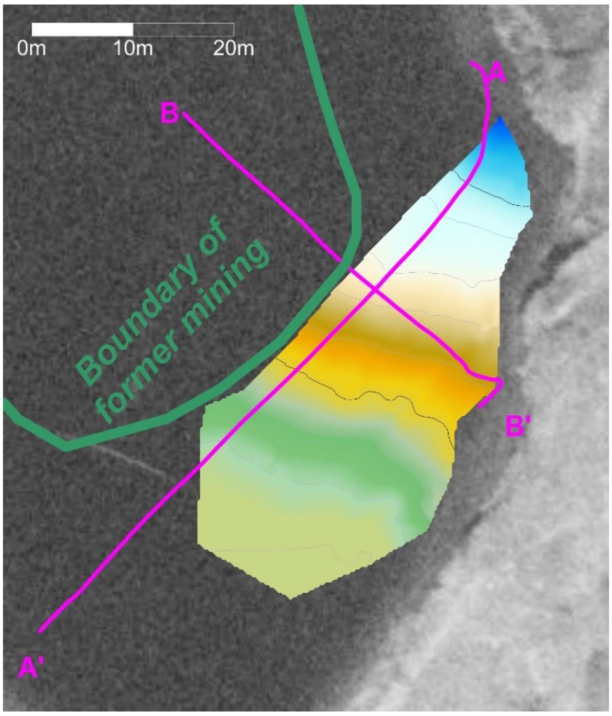

Figure 9. Mapped surface of a coal layer

Dip and position of the mapped coal horizon was compared with drilling information of historical boreholes drilled prior to the start of mining activity in the sixties. Depth and south-southwest dip of the clay and coal layers mapped on the lake seismic was confirmed by the drillhole information and could be incorporated into the geo-technical model.

4.2. Land seismic and electrical tomography profiles

The geophysical sections on land (both seismic and geoelectrical measurements) provided additional useful information for understanding the complex geology of the area, and correlating and interpreting the drilled core samples.

The sections indicate major differences between the western and the eastern part of the slope area. Conglomerates with P-wave velocities above 1200 m/s are characteristic of the western-nortwestern part of the slope area, while unconsolidated, low velocity layers are present in the shallow subsurface down to appr. 15 m below surface in the eastern-southeastern part of the slope. This is well visible in the NW-SE running seismic profile shown in Figure 10. Below the conglomerates a clayey layer appears based on the geoelectrical profile measured in dip direction (Figure 11). Core data also confirm the conglomerate body and the underlaying clay layer in matching depth interval.

The lateral and vertical variations imaged and mapped by the seismic and geoelectrical profiles were verified and complemented by drilling data and field observations. Geotechnical model was built based on the integration of all geophysical and geotechnical data and used for model calculations.

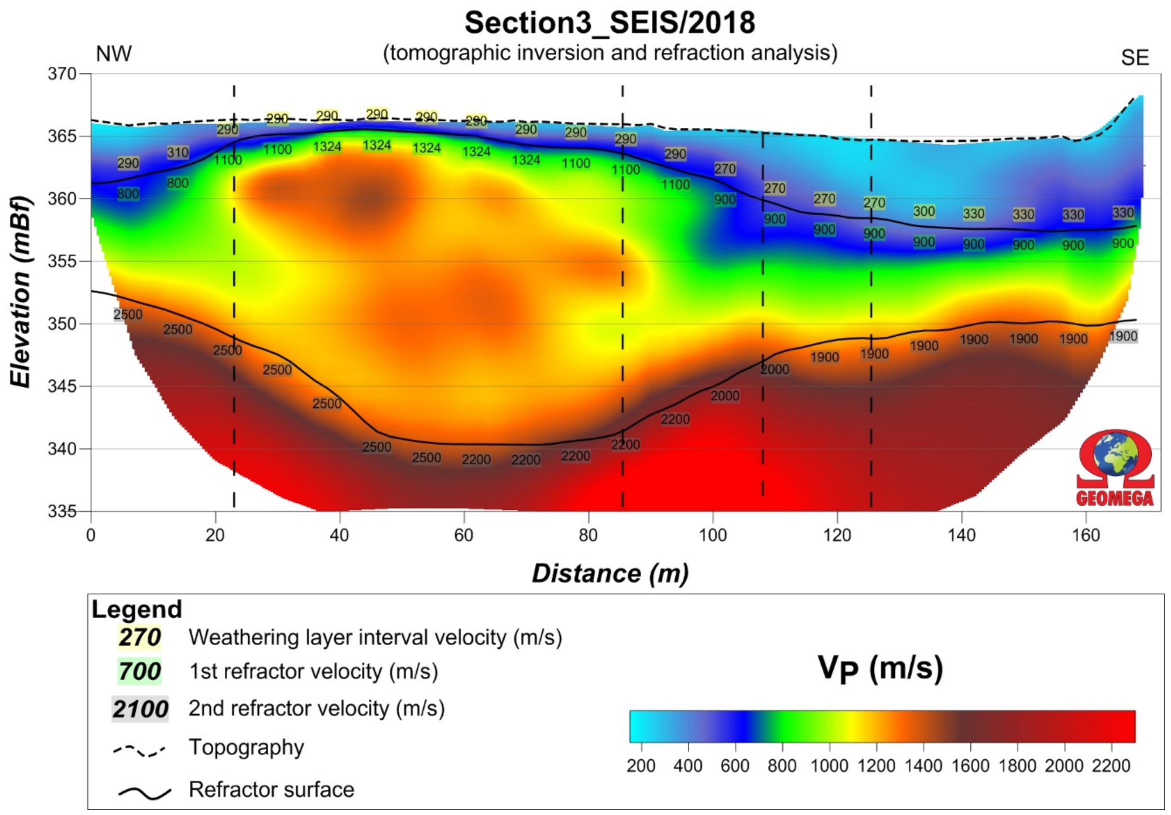

Figure 10. Tomographic inversion and refraction results of a seismic profile measured on the slope in strike direction.

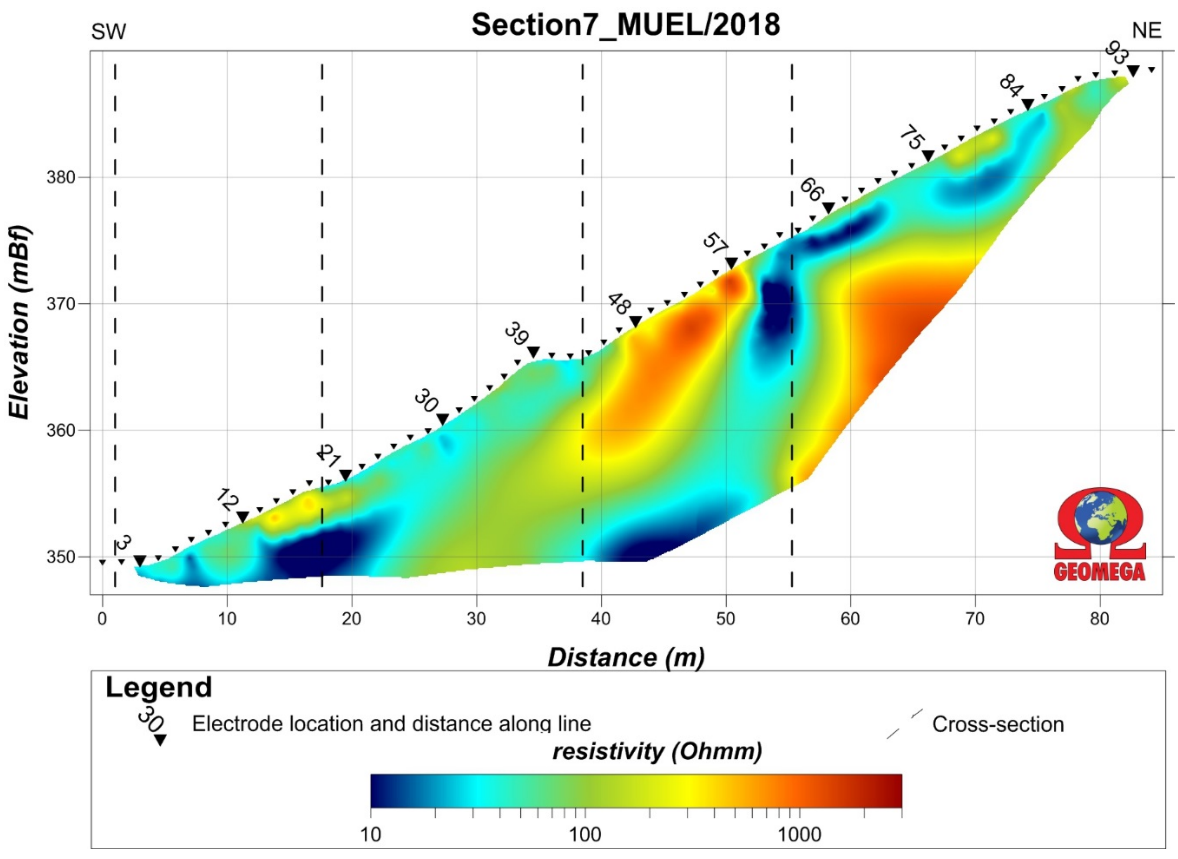

Figure 11. Dip-line geoelectric section showing apparent resistivity values along slope. Please note the low resistivity clay layers below the high resistivity

5. Geotechnical model

Based on the results of the geotechnical and geophysical investigations, the geotechnical sections of the slope was determined. The geotechnical properties of each layer were determined via laboratory tests.

Old mining maps were also used to determine the geotechnical model, which corraleted well with the exploration works.

The geotechnical model is shown on Figure 12. The layers marked red on Figure 12. represents peaty clay which is an organic, highly compressible stratum. The complex geometry of the soil layers was modelled using the hardening soil model in PLAXIS 2D.

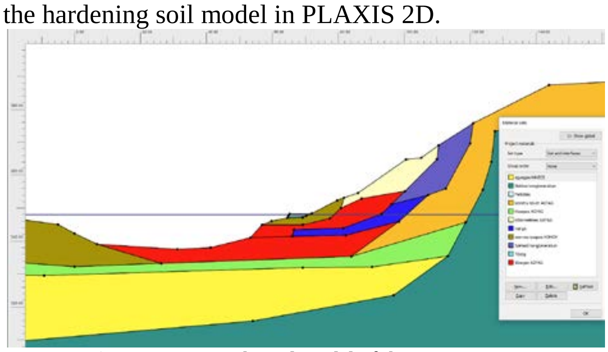

Figure 12. Geotechnical model of the existing state

6. Analysis of the existing state

6.1. Theory and software

In the geotechnical analysis, PLAXIS 2D v2016.01 finite element software was used for modelling of the most critical section in the middle part of the area.

Safety analysis was carried out according to the principals of Eurocode 7 DA-3 design approach.

The slope is considered stable, if the factor of safety (FS) is greater than 1,35, temporarily stable if the FS is between 1,00 and 1,35. If the FS is lower than 1,0, then the slope is not stable.

6.2. Results of the analysis for existing state

The calculations were carried out for the model described in chapter 5. The result of the calculation shows that the slope is not stable (FS<1,0). The displacement of the slope is shown in Figure 13.

Figure 13 shows a comparison of the surveyed and the calculeted displacements. The calculated displacements correlates well with the surveyed movements. It can be concluded that the geotechnical model was adequate, and models the behaviour correctly. The model did not reach equilibrium, therefore constant movement can be expected. To stop the movements, different solutions were proposed and analysed.

7. Possible solutions for stabilization

Several geotechnical solutions were considered and modelled in order to arrive at the best possible solution. Following modells were built and calculated:

1. Building a supporting land wedge in the lake below water level.
2. Creating a diaphragm wall at the feet of the slope.
3. Increasing geotechnical parameters of the debris peaty clay layers above the marl layer.
4. Increasing geotechnical parameters of the debris peaty clay layers above and below the marl layer.

Figures 14 and 15 show modelling results for the proposed solutions. Upper images in Figure 14 show the underwater ground wedge and the diaphragm wall built while the lower images show corresponding finite element models. According to the results of finite element model calculations none of these two reinforcement would ensure the required slope stability, in both cases FS<1,00.

Figure 15 shows two jet-grouting reinforcement (increasing geotechnical parameters) alternatives. In the first case jet-grouting is only applied to the upper layer above the marl (left), while in the second case it is applied to both above and below the marl layer (right). According to the modelling results jet grouting to both layer above and below the marl layer is necessary in order to stabilze the slope and prevent further movements. In this case the FS=1,39 > 1,35, therefore the slope can be considered stable.

The movements are expected to continue growing, but the cost of the latter solution is enormous. The area of the slope is isolated, so in our opinion it does not endanger human life or buildings. Therefore physical sealing with fences was recommended immediately, until decision is made about the engineering intervention.

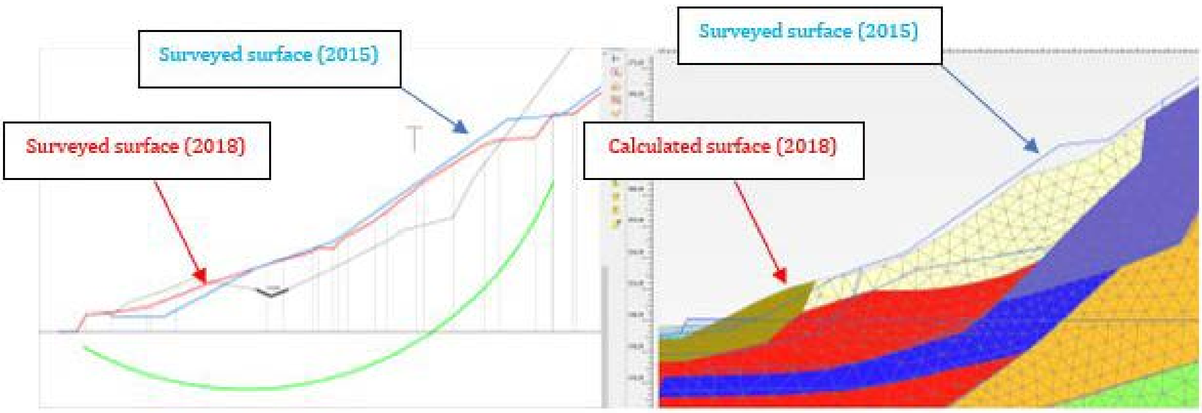

Figure 13. Comparison of the surveyed (left) and calculated (right) surface

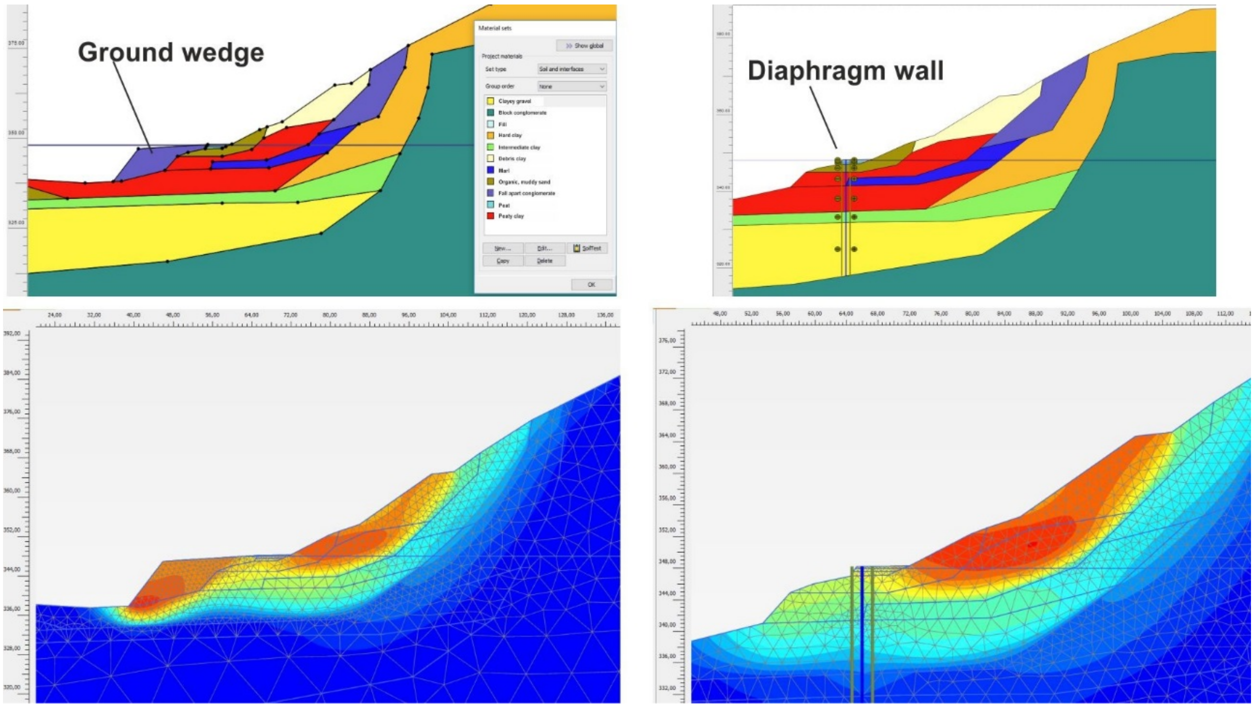

Figure 14. Ground wedge and diaphragm wall applied and corresponding finite element modeling results by PETIK Ltd.

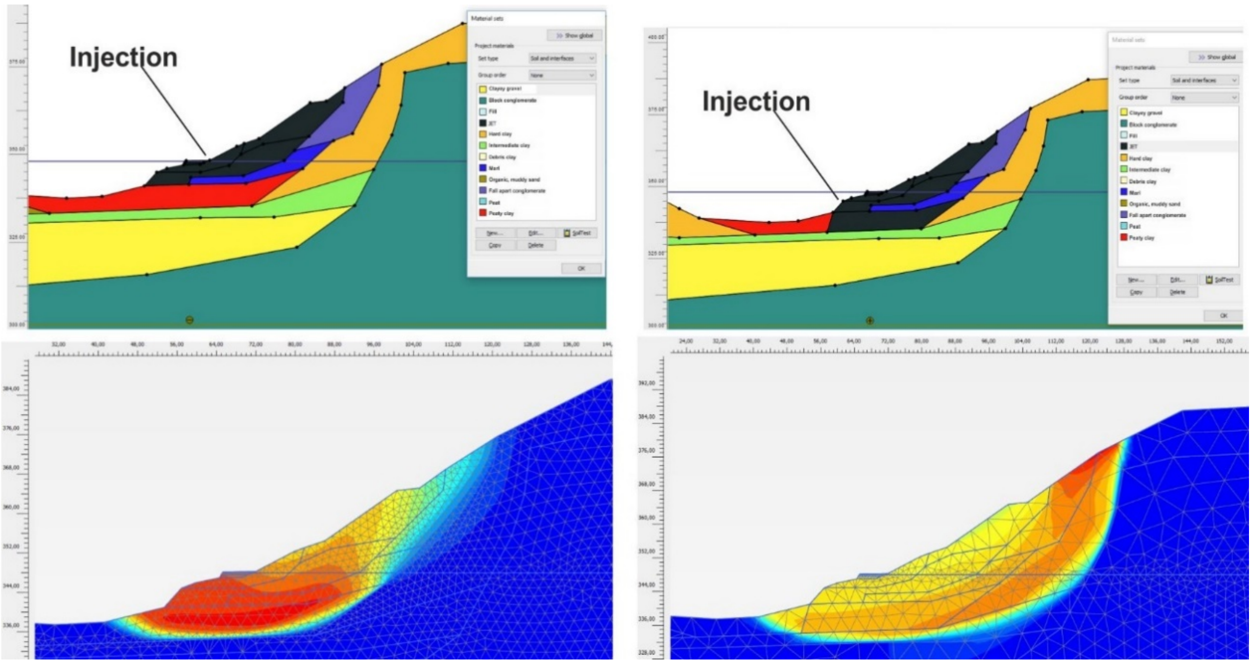

Figure 15. Jet injection in the upper layer only (left) and both upper and lower layers (right). Finite element modeling of PETIK Ltd indicates, that injection in both layers is necessary to stabilize the slope.

8. Conclusions

Complex subsurface structure, incomplete documentation of the prevoius mining and recultivation activity and the difficult surface conditions made a combined geophysical-geotechnical approach critical for the understanding of the problem and building an adequate geological-geotechnical model. Finite element calculations were based on this geological-geotechnical model and provided reliable feedback on different possible reinforcement technologies. Several of the possible reinforcement technologies were deemed inadequate based on the model calculations, however jet-grouting injection applied to both the unconsolidated layers above and below the marl layers could stabilize the slope.

The greatest advantage of the combined exploration works is that instead of point-explorations (borings) complete sections can be analyzed. This way the soil layers can be evalueted more precisely resulting in better modelling. Better models also help to understand the actual behavior more precisely, and help to determine adequate solutions for the engineering problems.

It should be noted however, that there are situations where combined exploration works cannot be used, for example well built-in cities. The considerable traffic and the electrical utilities and cables can make the use of electrical tomography impossible.

It should also be noted that explorable depth of the geophysical survey depends greatly on the length of the section. In city environment sometimes there is not enough space available for the proper section length and therefore for the appropriate survey depth.

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