Stability and movements of open-pit lignite mines in Northern Greece

Stabilité et mouvements de terrain dans les mines de lignite à ciel ouvert en Grèce du Nord

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ABSTRACT: This paper presents a case of a lignite mine in Northern Greece with excavated slopes exceeding 100-120m in depth in which substantial movement is occurring, with an average rate 10-20mm/day. The Mavropigi mine is very important for the power supply of Greece and uninterrupted operation is often critical, meaning that excavation is taking place on moving soil masses. The stability of the moving southeast slope is investigated and the information developed from an extensive monitoring campaign, with survey prisms, inclinometers and piezometers is presented. The use of the investigation data to evaluate the type of movement, the geometry of sliding surface and the effectiveness of remediation measures are analyzed in detail. The procedure of assessing the stability and safe slope operation during production, even with high rates of movement and the effect of precipitation are presented. It is shown that there are situations that mine slopes can move several meters laterally and still be operational without catastrophic failures.

RÉSUMÉ : On présente dans cet article une étude des mouvements de terrain dans une mine de lignite du nord de la Grèce. Dans cette mine à ciel ouvert de 100 à 120 m de profondeur, des glissements de pente (lents) sont observés : 10-20 mm/jour. L'exploitation de cette mine (Mavropigi) de lignite, primordiale pour la production d'énergie en Grèce, s'effectue sans interruption dans des pentes en mouvement permanent. Les problèmes de stabilité de la pente sud-est de la mine sont étudiés et les mesures effectués in situ à l'aide de différents appareillages (mesures topographiques, inclinomètres et piézomètres) sont présentés. L'analyse de l'ensemble des mesures est effectuée afin de caractériser le type de mouvement de terrain et la géométrie de la surface de glissement. Par ailleurs, l'efficacité des mesures adoptées pour stabiliser les pentes est analysée via les mesures effectuées sur le site. Une procédure permettant d'évaluer le risque de perte de stabilité pendant les phases d'exploitation (intensive) en tenant compte des effets défavorables des précipitations est proposée. On met ainsi en évidence des cas pour lesquels les pentes peuvent se déplacer latéralement de plusieurs mètres sans pour autant engendrer des ruptures majeures.

KEYWORDS: Slope movement, Coal open pit, Slope monitoring, Slope stability, Landslide.

1 INTRODUCTION

The Public Power Cooperation (PPC) operates a number of large open pit lignite mines in Northern Greece (Amyntaio-Ptolemais Basin). The Mavropigi mine has been mined since 2003 and at present the excavated slopes have reached depths exceeding 100-120m. Since 2011, the southeast slopes have shown persistent large horizontal movements at an average rate of 10-20mm/day, at times reaching more than 40-50mm/day affected by increased precipitation. The moving mass was estimated around 6Mm^3. This paper presents a case of significant movements that occurred at the southeast slope (Fig. 1), and details the monitoring, evaluation and mitigation measures taken to safeguard mining operations which had to be uninterrupted for production management purposes.

Figure 1. Southeast slopes of Mavropigi lignite mine.

2 GEOLOGICAL AND GEOTECHNICAL CONDITIONS

The Mavropigi mine is in the sedimentary fill of the Ptolemais basin which includes terrestrial and lacustrine deposits of Miocene up to Pleistocene age, with abundant lignite horizons (Diamantopoulos, 2006). Near horizontal intercalations of Marls, Lignites, Stiff Clays and Sands are the predominant materials; from a geotechnical point of view they can be described as "Hard Soils – Soft Rocks". The main intercalations are Marl and Lignite. The Marl material is mostly classified as Elastic SILT or Organic SILT (MH-OH) per USCS (ASTM D2487). Locally in the Marl – Lignite intercalations, thin (few centimeters thick) beds of High Plasticity CLAY (CH) are found. These almost horizontal thin beds have very low residual shear strength and often act as slip surfaces. The mechanical properties of the different materials encountered in the area of Mavropigi are presented in Table 1. These parameters are assessed from triaxial, direct shear and ring shear tests performed on selected core samples and are used for the slope stability calculations of the Mine.

Table 1. Range of Geotechnical Properties of Mavropigi Mine Materials.

Parameters / Materials	Marl	Lignite	Clay (CH)
Unit weight γ (kN/m^3)	16-18	11-13	16-18
Effective Cohesion c' (kPa)	50-150	150-200	5-50
Effective friction φ' (deg)	28-35	34-36	26-30
Residual Friction φ_r' (deg)	-	-	5-10

3 MONITORING OF SLOPE MOVEMENTS

At the end of 2010, tension cracks were observed at the crest of the Southeast mine slopes and visually observed horizontal transverse movements at the toe under prisms 5A3 and 6A4. Although this is usual in large and deep open pit mines, nevertheless, 20 prism monitoring stations, two inclinometers (KL-10, 11) and two piezometers (PM-10, 11) were installed on the slopes. The locations of the instruments are shown in Figure 2 together with the limits of the moving mass.

Prism measurement records were made available between January 2012 and up to the writing of this paper (Sept. 2012).

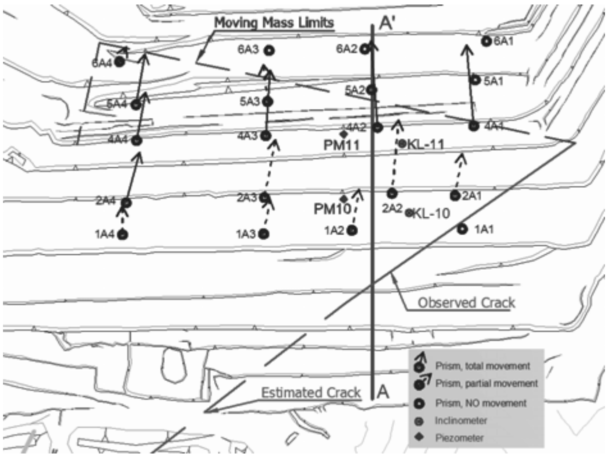

Figure 2. Monitoring equipment and trends on Southeast slopes

Initially the measurements were executed with a lower accuracy total station and only the "sloping distance" between the prism and the measurement base was evaluated. Due to the complexity and criticality of the situation, a new robotic total station of high accuracy (0.5cc) replaced the old one. With the new total station the movement vectors could easily be measured and evaluated. The use of the robotic total station eliminated the surveyor operation error and the high accuracy significantly reduced the horizontal and vertical angular measurement error.

Due to the high rate of movement, few measurements were taken from the inclinometers before they were sheared off. From inclinometer KL-10, six measurements were obtained in a period of one month which recorded a total displacement 100mm at 27m depth from ground surface. Inclinometer KL-11 recorded only three measurements in a period of 11 days, with maximum displacement 150mm at 9m depth. The two piezometers could only be measured twice due to operational reasons and recorded water table elevation at 18.4m in PM-10 and 9.9m in PM-11. A precise water table could not be estimated based on the piezometer measurements because of the number of measurements and since the faces of the slopes were found dry. Piezometric conditions and water pressures are very difficult to model with a high degree of accuracy in mines (Sullivan, 2007) mainly due to the presence of multiple perched aquifers. Figure 3 shows a geological cross section with the monitoring equipment and the failure surface location (white line). Dark zones indicate the lignite beds.

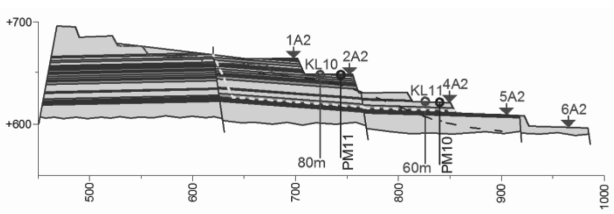

Figure 3. A-A' cross section with monitoring locations

4 EVALUATION OF SLOPE MOVEMENTS

The operation of Mavropigi mine is very important for the power supply of Greece and uninterrupted operation is often critical. Mining operations may take place even in moving slopes, as long as safety of personnel and equipment is satisfied. Zavodni (2000) states that "*mining operations can proceed safely with minimum interruption if failure mechanisms are understood and slopes are properly monitored*" even in moving slopes. The way to assess if a "moving slope" can be mined safely is to determine if the slope movement is regressive or progressive. A regressive movement is cyclic decelerated while a progressive movement exhibits overall acceleration without appreciable deceleration intervals (Zavondi, 2000). In regressive movements, mining operation can continue after incorporating a monitoring system. If monitoring data indicate a progressive type of movement the operations are in danger of imminent collapse. The question posed to the Geotechnical Engineer is to determine the type of movement that characterizes each particular slope. The failure mechanism needs to be understood and a sufficient quantity of qualitative measurements is required. In the literature, most case studies are analyzed after an incident and with adequate monitoring data and the type of movement is identified (Ryan & Call 1992). At the Mavropigi mine, decisions had to be made based on the day to day data becoming available without a priori having a large amount of data that could be used to determine the type of movement.

Initially, based on the geological model of the area, the visual observations of the cracks in the crest and the translational surface located by the inclinometers, a limit equilibrium model was analyzed to evaluate if the movement was possible and to back calculate the material properties of the shear surface. Based on back analysis (Figure 4) it was found that a sliding surface was possible with residual friction angle of $\varphi_r=7^o$ for the near horizontal surface and $\varphi'=24^o$ for the back scarp. These values were considered to be the lower bounds since no water pressures were introduced and were in good agreement with the laboratory ones provided in Table 1 for the area.

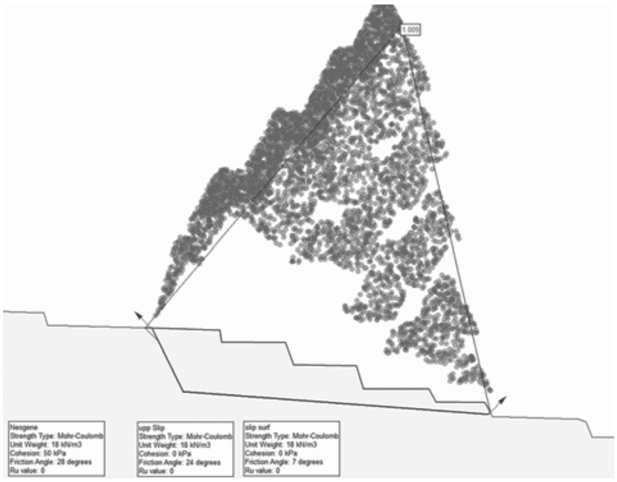

Figure 4. Back analysis of the sliding surface

From the geological model, the inclinometer readings and the back analysis it was found that the movement is taking place in a failure shear zone (thin high plasticity clay interlayer) with an inclination of about 4-5^o. Based on this information an initial estimate was made that the movement could be of the regressive type based on the recommendations by (Zavodi and Broadbent, 1980), by which movements are deemed regressive when taking place on a surface with a lower angle in relation to the slope face inclination and the shear resistance (friction angle) of the material. Initial remediation measures consisting of excavating part of the top two benches were analyzed with the same data. Analysis showed that the FS became 1.06 which was considered positive for reducing the rate of movement. The slope stability analysis was considered only indicative due to the complex nature of the sliding mass (fig 2) and greater emphasis was placed on slope monitoring.

The data were further analyzed to verify the regressive type of movement and to identify a possible onset of a progressive type of movement, leading to failure. One method to evaluate monitoring data is the inverse velocity measurement versus time. Based on this method, as described by (Rose and Hungr, 2007), when the inverse velocity of slope movement is plotted against time, failure is imminent as the trend line approaches zero values (velocity increases asymptotically). In Figure 5 the inverse velocity versus time is presented for prism 2A4.

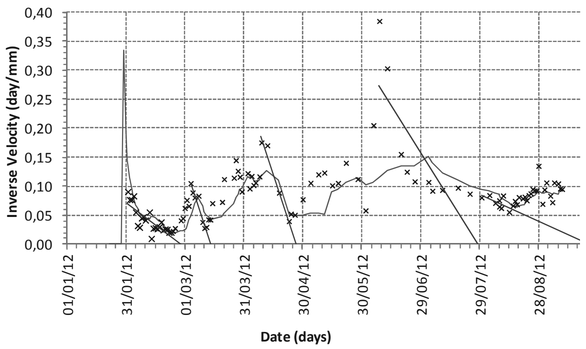

Figure 5. Inverse velocity versus time for prism 2A4

Figure 5 suggests that if this method is to be followed, at numerous times the mine slopes could be at imminent collapse. This is evaluated based on the extrapolation to zero of the regression lines for different time intervals (straight lines). For example the first imminent collapse could have been evaluated to have occurred on 01/03/12, which did not happen.

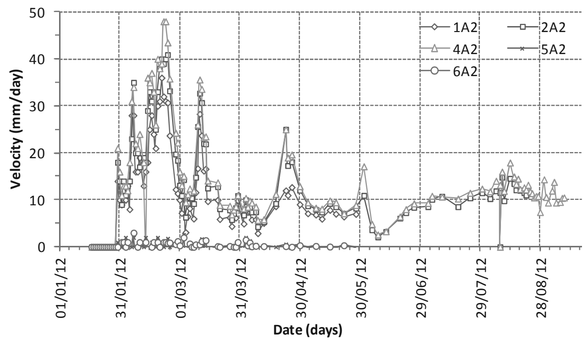

Figure 6. Velocity versus time for prisms of bench 2

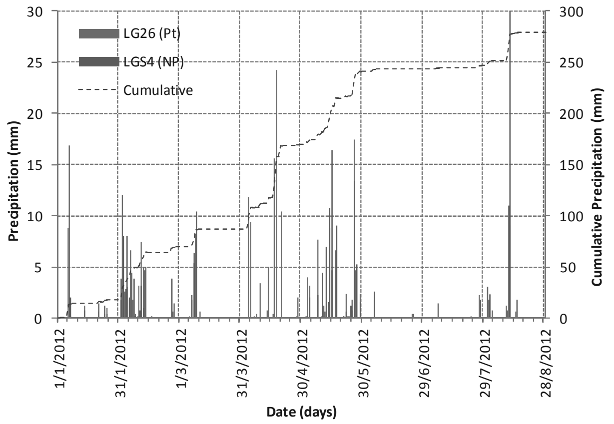

Figure 7. Precipitation versus time from two stations

Subsequently regression analysis presented times that failure could take place. This graph presents a situation where the method could not work properly without evaluating other critical factors such as precipitation or excavation unloading.

Figure 6 presents velocity versus time for all prisms of bench 2 while figure 7 shows the daily and cumulative precipitation for two weather stations. The mine is located in between these stations with a distance of about 7km. No precipitation data at the mine were available.

From the evaluation of figures 6 and 7, a strong correlation between the precipitation and the increase of velocity is observed. Further observation of figure 6 provides information of a stick – slip mechanism and a regressive type of movement in which the velocity does not increase or decrease at a constant rate but undergoes abrupt changes. During and after heavy precipitation the water filled tension cracks provide an increasing driving force. As displacement continues, the width of the cracks increase and the water level drops with a dissipation of water pressure. This is a repetitive situation which modifies the velocity of the sliding mass. Beginning of February 2012 limited (day shift) remedial excavation was executed on bench 1 and above to reduce the weight of the sliding mass. Such excavation increased after March 2012 being conducted on 24hour shifts. As a result movement velocities were reduced after that date.

In retrospect the movement was of the regression type (or behaved in this respect due to the excavation at the top of the slope) as can be seen from the displacement measurements at bench 4 presented in Figure 8. In this graph the displacement at the bench is plotted versus time for four different prisms in different locations transversally placed on the slope (Figure 2).

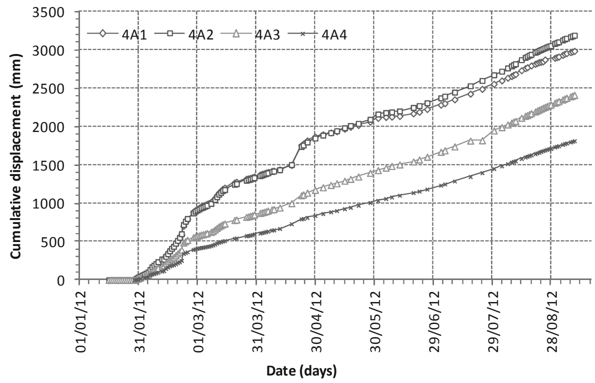

Figure 8. Cumulative displacement of prisms on bench 4

When the cumulative displacement becomes convex, movement acceleration is evident and a progressive type of movement can be inferred. When the cumulative displacement becomes concave then deceleration takes place. As can be seen from Figure 8 displacements "cyclically" change from convex to concave and back to convex meaning that this is of a mixed condition where the regressive type of movement prevails. Although the cumulative displacement of this slope for a period of 7 months is over 3m, the slope is still in a regressive type of movement and therefore mine operations continue.

5 GEOMETRICAL MOVEMENT INFORMATION

The dense grid of monitoring prisms together with the high accuracy of the robotic total station produced additional invaluable data for the moving mass. As can be seen from Figure 2 the vectors of motion are presented with arrows. The continuous arrows present monitoring information until the writing of this paper. The dashed arrows present monitoring data that were discontinued for operational reasons at different times. As can be seen from the arrows and the displacements at bench 4 (figure 8) the slope moves more to the east than to the west while both translation and rotation occurs at the same time. The reason for this complex movement can be explained taking into account the sloping surface geometry and the kinematic conditions of the adjacent southwest slopes.

The southwest slopes can be considered in a regressive moving condition as well. The movement there occurs at a very deep seated slip surface which is, partly formed on the schist bedrock probably on top of an old "inactive" fault and partly on the Neogene formation. The movement of that deeper slide may be generating lateral forces that are applied on the moving mass at the southeast mine slopes.

The complex movement of the southeast slope is also affected by the inclination of the sliding surface where the southeast slopes are moving on. As was shown previously in section A-A' the shear surface was found to have an unfavorable inclination of about 4-5^o. This unfavorable situation is not continuous transversely across the slope. This can be safely stipulated after careful evaluation of the vertical – horizontal displacement of different prisms in the same bench (figure 9). In this plot the abrupt change of measurements is due to maintenance of the prisms.

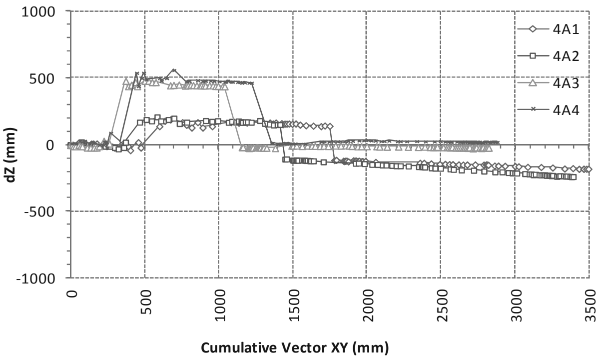

Figure 9. Vertical versus horizontal displacement

As can be seen from figure 9 and especially after about 1500mm of horizontal displacement, when no abrupt changes are recorded, the prisms at the east (4A1, 4A2) produce a downward movement with an angle of about 4-5^o. The 4A2 prism which is located at cross section A-A' produces the same shear surface inclination as determined by the inclinometers. Further to the west the sliding surface becomes horizontal or even with slight favorable inclination. This sliding surface geometry is responsible for the increased movement to the east and the rotation of the moving mass.

This detailed evaluation of the moving mass could not be possible without the dense grid of measuring points and the high accuracy of the robotic total station. It is evident that with accurate monitoring data shear surface inclinations can be evaluated from surface measurements.

6 CONCLUSIONS

A case study of high horizontal movements recorded on operational surface mine slopes has been presented. The slopes have been moving with an average velocity of about 10-20mm/day and until today they have moved more than 3m.

The sliding mechanism was investigated and, based on back-analysis, it was determined that the southeast slopes of the mine are moving on top of a near horizontal shear surface with a residual friction angle of about 7^o. As no water pore pressure was used in the analysis, this value is considered a lower bound, and coincides with values determined through lab experiments for similar material in the mine area. The slope stability analysis is considered only indicative due to the complex geometry of the moving mass. It is not possible to exactly model this mass with plain strain limit equilibrium methods.

Great emphasis was given in the monitoring program in which twenty prisms, two inclinometers and two piezometers were used. The surface monitoring of the prisms was greatly enhanced when a high accuracy robotic total station was used. With the high accuracy of the robotic total station, movement vectors could easily and accurately be measured.

The measurements presented a complex type of movement of the slopes which most of the time was of the regressive type. The slope movement has been found to be greatly affected by the periodic precipitation and the infilling of the tension cracks.

Based on the regressive type of movement, the mining operation could continue and at the same time remedial measures taken with excavation of the top benches for unloading. This remediation decreased but did not stop slope movements. Although the slopes have moved more than 3m horizontally, they are still in operation without significant problems. Movements were found to be very sensitive to external conditions such as precipitation.

The increased accuracy of the prism measurements allowed the identification of the sliding surface inclination along the mine slopes. It was found that the sliding surface changed inclination transversely.

High mine slopes can be in operation even if they produce high rates of movement, as long as the sliding mechanism type is identified and continuously monitored. Remedial measures can be incorporated in the mine plan in order to reduce movements.

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