Ground Deformation Monitoring Techniques at Continuous Surface Lignite Mines

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ABSTRACT

Several methods for monitoring ground deformation at surface lignite mines have been developed. The Public Power Cooperation (PPC) lignite mines in Western Macedonia and Megalopolis are being constantly monitored by applying several of these methods. This paper presents the methods that are currently implemented and the reasoning behind their selection. Mine planning, mine size, time constraints, expected magnitude of movement, terrain morphology and geology dictate the monitoring scheme.

The vast majority of the measuring techniques can be classified as local and they tend to be more economical and easier to implement. These methods include GNSS, high accuracy Total Stations, borehole inclinometers, structure tilt-meters and borehole settlement meters. Satellite InSAR, aerial photography and most importantly continuous experienced eye observation can be categorised as global techniques which can give a general overview of the monitored area. They can be used for early warning of slope deformation that requires closer, ground – based measurements. Some of these data collection techniques can be automated, or do not require highly skilled personnel.

This paper aims to categorise monitoring techniques into local and global. Furthermore, the main advantages and disadvantages of each technique are presented.

Taking into account that the measurements are far from homogenous, a cloud-based real-time slope movement monitoring system (GIS) is also presented. This built-to-order system has been developed for the evaluation of the observations, by automatic generation of tangible reports.

I. Introduction

In the last few years a growth of renewable energy technologies has been observed. However, lignite is a significant domestic fossil fuel resource in Greece, and also an important component of Greece's energy security. Currently lignite contributes about 30% of domestic electricity demand (Roumpos et al., 2018).

The main lignite deposits under exploitation by Public Power Cooperation (PPC) are located in the Ptolemais - Amynteon basin, in the area of Western Macedonia, in northern Greece and in Megalopolis region, in Peloponnesus, southern Greece. Greek lignite deposits have a multiple-layered structure consisting of several lignite layers separated, mainly, by waste beds. The necessity of selective mining because of this stratigraphic deposit structure, combined with the requirements for high production rates, was the reason for the application of the continuous surface mining method. Large bucket - wheel excavators and spreaders, as well as a network of conveyor belts to transport the lignite to power stations and the waste material to dumping sites are the central infrastructure of the implemented mining technique. This surface mining method produces a very characteristic landscape (Figure 1).

Figure 1. Typical excavations face of continuous surface lignite mining.

The bucket - wheel excavators continuously advance creating benches (60-120 m wide) and drops (15-25 m high). The resulting slope has an overall inclination (v:h) between 1:4 and 1:7 (Kavvadas et al. 2018).

The Ptolemais - Amynteon Lignite Field is developed in a ca. 150 km long and ca. 15-20 km wide tectonic graben (basin), up to 200 m deep, which extends in the NNW-SSE direction. The Megalopolis Lignite Field is smaller in extent (ca. 40 by 10 km) and thinner (up to

100 m deep), has similar geologic history but developed at a later geologic era. Both sites present stability issues related to their geological characteristics or to their lower shear strength (Kavvadas et al. 2018).

However, regardless of the geological characteristics of a surface mining field, the existence of the excavation and the dumping slopes ensures ground deformation in continuous surface lignite mines. The scale of the mining works as well as the magnitude of earth moving volumes inevitably results in motion.

In this work, several methods for monitoring this motion are presented. Their main characteristics, their advantages and disadvantages as well as the reasoning of their application in PPC's continuous surface mines are discussed. Other authors have also assembled techniques of monitoring open mines (Narendranathan & Nikraz, 2011, Settles et al., 2008).

In this work, the techniques of ground monitoring at continuous surface mines are categorized as local or global. Local monitoring techniques assess the dynamic behaviour of individual points or small regions of the mines. In contrast, global monitoring techniques assess the mine and its surrounding area, as a whole. Techniques that monitor single slopes are considered as local, because an excavation or a dumping mine slope, regardless of its size, constitutes only a small part of the mine. A graphic representation of this categorisation, considering also the cost, can be seen in Figure 2. The categorisation of monitoring methods into local and global is not novel (Vaziri et al., 2010).

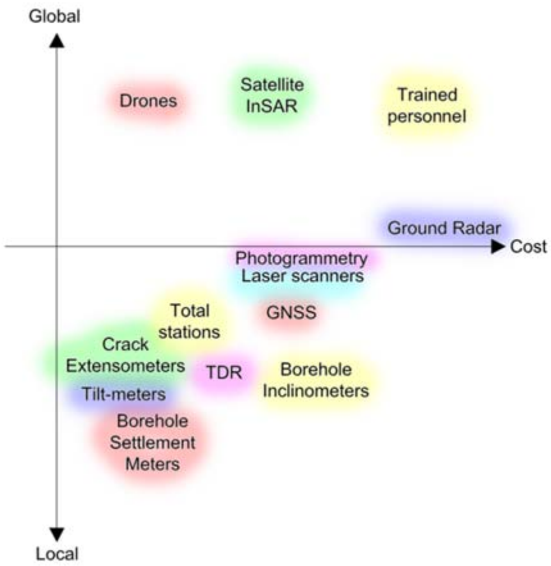

Figure 2. A graphic representation of the deformation monitoring techniques presented in this paper.

The accuracy requirements for mining purposes are much more lenient compared to the corresponding of other civil works. An accuracy in the order of 10 cm is in most cases sufficient. It should be mentioned, however, that this only refers to the absolute position of discrete points. If the goal is to determine the velocity of a point in order to estimate the probability of a slope failure, then an accuracy of a few millimetres is necessary.

II. LOCAL MONITORING TECHNIQUES

A. *Total stations*

The prospect of using total stations for monitoring purposes is obvious. A monitoring system using total stations consists of two main components. The points of interest are marked by the installation of retroreflective targets (corner reflector or cat's eye). These are typically well anchored to the ground and a large number of them are spread out on the slope.

A total station placed either on a predefined point or a random point observes all the points measuring horizontal and vertical angles as well as the slope distance. In this work theodolite observations are not described as a separate technique since in recent years the cost difference between the theodolites and total stations is very small. Also the ability of measuring slope distances allows a monitoring scheme where only distances are measured.

If the total station is set up on a predefined point, then it is usually assumed that this point's position is stable. This approach is rather easy to implement and leads to an internally consistent result. On the other hand, if a random point is chosen for each epoch of measurements, then it is necessary to determine the position of this random point, prior to the measurement of the points on the slope. The latter approach defines the target point position in relation to an external coordinate system. This allows monitoring of the points in relation to a system that can be considered stationary. Note that any miscalculation of the total station position is passed on to all points of that epoch as an error.

The aforementioned procedure can be altered in order to cover the required accuracy. Low cost total stations and non-predefined targets will produce a low accuracy result quickly. This might be very useful in demanding situations of an imminent failure. Of course high accuracy systems are also available. These usually consist of precision robotic total stations that automatically measure preinstalled targets (wah Leung, 2003).

Due to their cost, robotic total stations are usually installed in a protective shelter and measurements are carried out through a glass pane. The effect of the glass on the distance measurement has been studied by Afeni & Cawood, 2013.

The previously mentioned cost extremes only define the borders of the available systems. However, common practice lies somewhere in between. Systems and measuring regimes that have a reasonable cost and that yield the necessary accuracy have been proposed (Zahariadis & Tsakiri 2006).

Total stations are used for monitoring the continuous surface lignite mines operated by PPC in Western Macedonia and Megalopolis areas. Pre-installed station positions have been erected and a total station with auto-lock function is placed at these positions. The auto-lock function reduces any targeting error by measuring in a uniform manner. From each position and at each epoch, a number of corner reflectors are measured. In certain cases, the viewing distance is large (about 4 km), restricting the available hardware that can reliably perform auto-lock.

Due to the dynamic environment of the mines, some targets are unfortunately destroyed. In these cases, new targets are installed and measured. In spite of this, monitoring with total stations is considered to be an accurate and reliable technique. More information concerning the accuracy of total station measurements within a mine can be found in Chrzanowski and Wilkins (2006).

PPC uses total stations as a backbone of slope monitoring. The relation between cost, robustness and accuracy is the obvious reason for using total stations for earth deformation monitoring. Another, equally important reason is the fact that that human presence is not required at the target location. This allows monitoring regions of the mine that are considered as dangerous.

B. *Global Navigation Satellite Systems (GNSS)*

Discrete points on the surface can be measured using Global Navigation Satellite Systems (GNSS). The main advantage of GNSS observations is that they refer to a consistent global geodetic system. This can assist in assessing the absolute position and thus the deformation of the ground. Brown et al. (2007) also state that GNSS hardware is more suitable and robust for continuous surface mines, due to the absence of moving parts. Also their tolerance to dust and rain contributes even more to this.

On the other hand, the drawback of using GNSS is that as a method it requires the human presence. This may be dangerous in the case of an imminent slope failure or even totally impossible if the goal is to measure points on a slope face.

The accuracy of GNSS is sufficient for monitoring ground deformation at lignite mines, even when using RTK. As mentioned before the necessary position accuracy of discrete points is in the order of 10cm. This is especially valid for GNSS observations since the result refers to an external stable coordinate system.

In cases of imminent slope failure though, this is a limiting factor for GNSS. RTK observations cannot be carried out since sub-centimetre accuracies are required in order to calculate ground velocities and predict the time of failure, or the lack of it.

C. *Laser scanners*

Measuring points via two directions and a distance is the main principal that total stations use to calculate 3D positions of targets. The same principal can also be carried out using a laser scanner. The main difference is that laser scanners don’t measure discrete points, but points on a predefined angular grid. The outcome of this procedure is a point cloud that then gets triangulated and a surface is generated.

In order to monitor ground deformation, surfaces from two epochs are generated. The alignment of these surfaces is either known beforehand by placing the scanner on the same point for every epoch, or can be determined by comparing the surfaces of each epoch (Akca, 2007, Prokos et al., 2011). The differences between the surfaces are contributed to deformation.

Time of flight (TOF) laser scanners are used since other scanning techniques[1] cannot measure the distances and scale of a mine. TOF scanners can measure points on a grid of few centimetres from a distance of several hundreds of metres. Due to the maximum measuring distance of most laser scanners, they have been categorised as a local monitoring technique. It should be however mentioned that a small number of scanners can resolve distance over 4 km.

D. *Photogrammetry*

Surfaces can also be generated by means of photogrammetry. Points that are depicted on at least two photographs taken from different positions can be triangulated and their 3D coordinates calculated. Accuracy is mostly depended on the ratio between the distance between the two photographs (base) and the distance between photographs and the slope (height). Acceptable ratios are in the order of 1/3 which again limits the measuring distance.

If the images are acquired with a drone, then the exterior orientation of the photos becomes the limiting factor. All errors of the exterior orientation carry through to surface points. A typical drone mission will produce ground accuracy in the order of 10cm. This is one of the limiting factors of the method, for the same reason as described for RTK GNSS techniques.

E. *Ground Based Radar*

The most common way of measuring surfaces within a mine environment is through means of Radar technology. Radars omit their own light source, allowing the depiction of subjects that cannot be viewed within the visible portion of the

[1] Phase shift scanners are rarely used in continuous surface lignite mines to monitor deformation since their range is rather small, within the order of a few hundreds of metres.

electromagnetic spectrum. Clouds and other weather conditions don't prohibit the visualisation of the subject.

In addition, since the omitted radiation is chosen, two separate measurements can be carried out. The first is the amplitude of the received pulse. Generally smooth surfaces and calm water tend to appear dark in radar images and rough surface, water in windy days and human-made objects appear bright. Special targets can also be tailored in order to ensure high amplitude numbers. The second is the time it takes for a pulse of radiation to leave the radar, bounce off the subject and return to the receiver. The speed of light is known and thus the distance between the radar and the subject can be calculated. Usually the phase difference between the omitted and received pulse is stored allowing the calculation of deformation between two or more measurements. The end result for each measured point is a complex number combining the amplitude and the phase of the received pulse (Fletcher, 2007).

Ground based radars can be tailored to carry out different types of observations. When scanning individual points, usually a Real Aperture Radar (RAR) with a parabolic antenna is chosen. Each point is measured by rotating the antenna, sending and receiving a number of pulses. These types of radars are chosen when a particular slope needs to be monitored, usually when the slope is suspected of failure (Harries et al., 2006). The accuracy in the direction of the line of sight is very high, commonly sub-centimetre.

On the other hand, Synthetic Aperture Radars (SAR) usually measure surfaces, producing instantly an array of complex numbers (pixels) depicting the slope.

The authors categorise ground based radars also as a local technique since the entirety of the mine cannot be monitored from a single position. It is however, a technique that allows observation of a whole slope or even a small number of them.

In the case of continuous surface lignite mines, deformations can usually have a lager magnitude than the half-wavelength of ground based radars. Since deformation is calculated by analysing phase difference, large motions will be impossible to measure due to the undetermined number of lost wave cycles.

These reasons, local measurements, deformation calculation only at the line of sight and resolution lager than movement, combined with the significant cost of ground based radars, has led PPC to, for the moment, not use them as an operational technique.

F. *Tilt-meters*

Tall structures around continuous surface mines are obviously affected by the mining activities. Differential earth subsidence causes structures to lean. This can be measured using tilt-meters.

There are several structures near the lignite mines of PPC that are of interest. Mainly the old Ptolemais thermal power plant (green position in Figure 3) is currently been monitored using tilt-meters due to its proximity to the Mavropigi mine. Monitoring has revealed that the cooling towers have been affected by the mining activities.

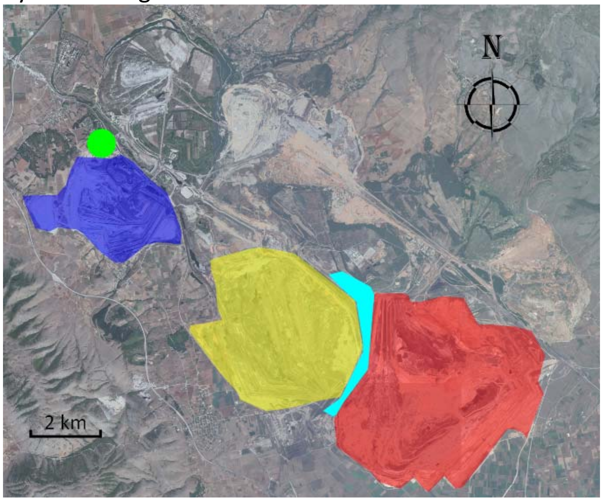

Figure 3. The Ptolemais Field continuous surface lignite mines at approximate position 40.45N, 21.80E.
Blue indicates the Mavropigi mine,
Yellow indicates the Kardia mine and
Red indicates the South Field mine.
Green indicates the position of the old Ptolemais thermal power plant that is monitored by Tilt-meters and
Cyan indicates the route of the planned new road and railroad on old deposits that are monitored using Borehole Settlement Meters.

G. *Crack Extensometers*

In cases of surface cracks, extensometers can be placed in order to monitor the development of the crack. These devices consist of three parts. Two anchors are placed on either side of the crack and a steel tape spans the distance. Differences between measurements on the tape are attributed to the expansion of the crack.

H. *Borehole Inclinometers*

Up until this point, all described methods have relied on measurements taken from the surface. Movement of the underlying geology has been assumed to translate to the top and has otherwise been neglected. Borehole Inclinometers, Time Domain Reflectometry and Borehole Settlement Meters actually measure phenomena that occur below the surface.

Some boreholes are fitted with a casing constructed of PVC. The casting creates two tracks at a right angle that guide an inclinometer. Readouts are carried out at predefined depths and a typical measurement involves four sessions, acquiring readouts separated by 90°.

The initial measurement is considered to be the base epoch and all succeeding measurements manifest deflections below the surface. Since measurements are carried out in two orthogonal directions, the deflection can be mapped in 3D. The result of such readouts can be seen in Figure 4 where a borehole inclinometer near the Amynteon mine has been plotted and data from 27 different epochs are represented using colour-codes.

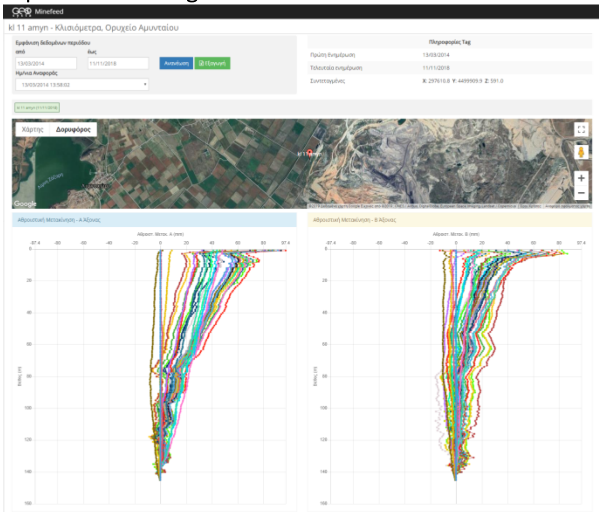

Figure 4. A screen shot of the GIS mentioned in section IV. Here borehole inclinometer near the Amynteon mine, from two axes has been plotted. The colours represent different epochs.

I. *Time Domain Reflectometry (TDR)*

A very economical method of monitoring the deformation of the underlying geology is Time Domain Reflectometry (TDR). The main component of TDR is a simple coaxial cable. Analysing the response of voltage pulse sent down the cable, it is possible to determine the distance at which the cable has been deformed. The principal is simple and has been analysed by Kane et al., 1996. The impedance characteristics of a coaxial cable change when the cable is deformed.

Installation of TDR cables consists of burring the cable in a borehole, using grout that matches surrounding geological characteristics. The reflections of voltage pulses at deflection points show up as a detectable peak in the trace and the depth of deformations can be determined. A data collector and transponder can also be attached to allow remote monitoring. Automatic analysis or the data is also feasible (Farrington & Sargand, 2004)

In comparison to borehole inclinometers they are much easier and cheaper to install and can be monitored constantly and remotely. However, they cannot provide the direction of movement but only the distance from the surface. In order to estimate the direction, TDR measurements have to be combined with other techniques and a model of the underlying geology has to be generated.

The inability of TDR to produce 3D maps of the deformation led PPC to the selection of borehole inclinometers for estimating the underground deformation. Lignite mines are not geographically spread out. This allows a surveyor with a single inclinometer to take measurements at multiple boreholes each day, leading in selecting inclinometers over TDR for lignite mines.

J. *Borehole Settlement Meters*

Deformation also occurs in waste dumping areas. The main motion of dumping sites is settlement. This can be measured as a total on the surface, by using the typical techniques outlined previously. However, using borehole settlement meters it is possible to measure the settlement of each underlying layer.

It is common practice to further develop regions of a mine that have been used in the past for waste dumping. However, development should happen once the dumping areas have sufficiently settled. Borehole settlement meters can be used to predict the time at which, development can begin. A good example of this is the planned railroad line between Ptolemais and Kozani. The new line will be placed on an inside dumping area between the Kardia and South Field mines (cyan area in Figure 3). The dumping area must have sufficiently settled and then the line can be installed. Observations from borehole settlement meters allow a better estimation of the time at which the railroad works can safely begin.

Figure 5 presents some different ways in which borehole settlement meters can be represented. The upper right plot shows the depth of measuring devices within the borehole. Differences are obviously too small to show. However, the lower plots depict, on the left, the depth difference and on the right the accumulative settlement.

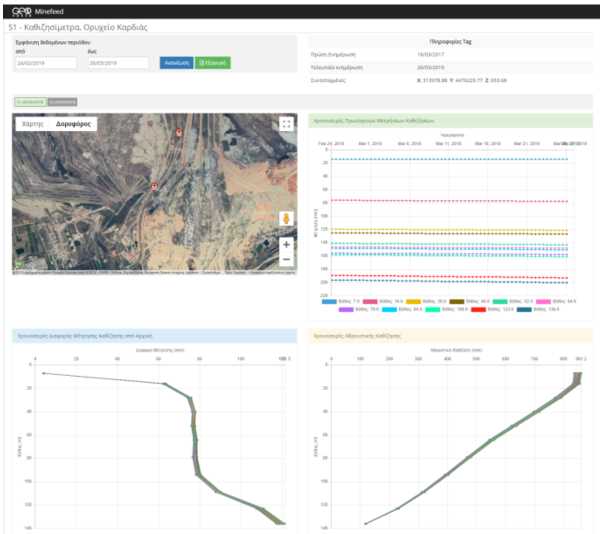

Figure 5. A screen shot of the GIS mentioned in section IV. Borehole settlement meter on the waste dumping area between the Kardia and South Field mines is presented. The colours represent different depths.

III. Global Monitoring Techniques

A. *Trained personnel*

Trained personnel may be the most important aspect of a monitoring system. An experienced mine worker can estimate regions in the mine that are unstable, for personnel or for vehicles. This is done mainly through optical observations of cracks on the surface, unusually high water content in certain region or even ground response to heavy equipment.

This is a non-quantifiable ability that develops over time. It is highly regarded within PPC since many of the employees are very experienced. Here it is categorised as a global technique since human activity is spread throughout the mine, even though, in most cases, each observation refers to a small region of the mine.

B. *Drones*

Trained personnel, as mentioned before can locate areas of potential hazard while conducting other work in the mines. This can be systematised by implementing regular drone flights. Images captured by drones can be assessed by trained personnel using simple photo-interpretation techniques in order to have greater land coverage.

The continuous surface mines developed by PPC use drones in order to assess the progress of mining. The outcome of the flights is a shaded point-cloud and usually an orthophoto. The examination of this outcome can reveal areas of the mine that are undergoing deformation.

C. *Satellite InSAR*

Satellite radars operate using the same principals as ground based radars. Due, however, to the distance between the radar and the subject, Synthetic Aperture Radars (SAR) dominate the field and the main analysis that is carried out is Interferometry (InSAR).

The most accurate way to measure small changes in the signal phase of radar images is to combine two of them by creating an interferogram. Given a position on the ground, i.e. a pixel on the radar images, the phase of the two images will either amplify or cancel each other.

The interferogram is produced by colour-coding areas of the image according signal amplification or cancelation thus colour-coding the area of interest.

Consequently, regions undergoing deformation will in general be represented with a series of concentric colour zones, called fringes, in an approach analogous to the elevation curves of a topographic map. Each fringe to fringe section represents deformation equal to half of the wavelength of the radar signal in the line of sight direction. In order to determine the total amount of ground movement between the two epochs, it is sufficient to measure the number of interfering fringes.

If no large-scale spatial deformation has occurred between the two images, two epochs, then a DEM can be generated.

Alternatively, if a precise digital terrain model is available, removing the contribution of the ground morphology from the signal phase of each image, allows the extraction of information relating to ground deformations between the two epochs. The last process produces detailed depictions of deformations, with a precision in the order of millimetres for areas up several square kilometres (Helz, 2005).

In practice, a large number of satellite radar images (time – series) are fed to an algorithm that produces the end result of the interferograms (Osmanoğlu et al., 2016).

Notable advantages of satellite InSAR is the relatively low cost and large area coverage. However, this technique also carries some of the drawbacks of its ground based counterpart. Manly the fact that deformation calculation is available only at the line of sight direction and that usually alterations within a continuous surface lignite mine have a magnitude lager than the half-wavelength of the radars (Zhou et al., 2009).

Despite these disadvantages, the knowledge of deformation in a neighbouring region to a lignite mine is indispensable and thus further attention can be given to these regions. For this reason, PPC has occasionally ordered InSAR analysis from contractors. Figure 6 shows one result of the analysis. In 2010, cracks started to appear near the Mavropigi mine. Retrospectively, using InSAR data, deformation was detected two years prior to the surface crack formation.

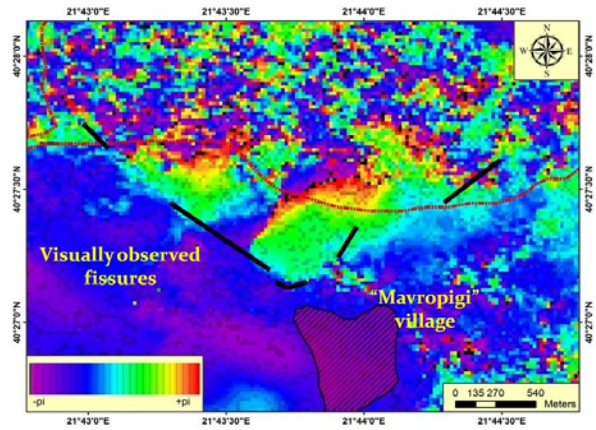

Figure 6. The wrapped interferogram covering the period 25.03.2008-31.03.2010 of the region near the Mavropigi mine (from: Papadaki et al. 2013).

IV. GIS

All methods previously mentioned give results far from homogenous. Both local and global techniques that have been presented; surface and underground monitoring systems are working in tandem with each other to enable engineers to monitor ground deformation. Inherently, the procedures come with their own way of presenting results. This inconsistency led PPC to invest in a software solution to unify the techniques. The result is a built to order GIS. It is a cloud based data management system, available both as a Windows application and as a browser based application (Steiakakis et al. 2018).

The GIS is able to import data from various input files. Output visualisation is customisable for each user of the system and consistent between monitoring techniques. Tangible reports are generated automatically and also warnings and alarm notifications are automatically sent to users that have selected the specific setting. Examples of these reports and graphs are shown in Figures 4 and 5.

All the data stored on the system is available at all times for download and further analysis. Users have set read – write permissions on the data.

V. Conclusions

Continuous surface mines, developed for the exploitation of lignite deposits with complicated structure, constitute complex and continuously varying operations. Taking into consideration the development of the mines, deformations are always inevitable. They are also related to the geological characteristics of the deposits. For monitoring ground deformations, PPC has invested in suitable available techniques which are discussed in this work. Most of these provide deformation results for discrete surface points and in order to estimate the behaviour of an excavation of dumping slope, many observations are required.

Despite the application of the applied methods for monitoring earth deformation, slope failures have occurred. PPC constantly takes action in order to minimise the risks by using the previously mentioned monitoring schemes. The main goal is of course to prevent the loss of life. This goal has been achieved within the last years of constant mining activities.

Deformation monitoring is only one aspect of hazard management for PPC. All the methods mentioned in this work require investment and the benefits are not immediate. It is however the economical and safe way to save lives, equipment and mining works.

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