LOW COST MONITORING SYSTEM IN THE OPEN PIT LIGNITE MINES OF MEGALOPOLI, GREECE

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Abstract: Continuous monitoring is critical to ensure safety of the stability of open pit mine walls. However, the cost of using off-the-shelf monitoring systems is prohibitively expensive, particularly for small-scale deformation surveys. The notion of this paper is to describe a low cost monitoring system that is successfully implemented in the open pit lignite mines of Megalopoli in Greece and discuss the issues influencing the accuracy of the system. The processing scheme is described and emphasis is placed on the atmospheric correction of the raw measurements. Results are given from a real scenario whereby the deformation rates as estimated from the above surveying measurement scheme indicated slope failure and appropriate preventive measures were taken in time to restrain collapse of the pit.

1. Introduction

The stability of steep slopes in open pit mines is a major safety issue because, in many situations, measurement of small, superficial displacements can provide the precursors necessary to predict catastrophic failure. The aim of continuous monitoring is to estimate the velocity of the slope's motion in order to detect critical displacements before it reaches its failure point. Whilst a reliable monitoring system allows for early measures to be taken in order to avoid the failure and to give the opportunity for personnel and equipment to evacuate the working area, the unreliable monitoring system may cause false alarms and costly stoppages in the mine production [1].

Typical slope monitoring systems comprise a combination of geotechnical sensors and surveying instruments while recent systems implement new techniques from GPS permanent stations to radar interferometric data, e.g. [2], [3], [4]. Surveying techniques are almost always implemented in open pit mines regardless of other sensors that may be used in combination, because of the reliability and accuracy that is offered by the surveying instruments. Today robotic total stations are routinely used in a fully automated way as the primary measuring device combined with meteorological sensors and interfaced with computers and wireless communication facilities in order to transfer the data to the processing centre, e.g. [5], [6].

However, the cost for off-the-shelf robotic systems that are commercially available for continuous monitoring is prohibitively expensive, particularly for small-scale deformation surveys. The notion of this paper is to describe a low cost monitoring system that is successfully implemented in the open pit lignite mines of Megalopoli in Greece, discuss the issues influencing the accuracy of the system and demonstrate this with a case study.

The three lignite mines in Megalopoli are operated by the Greek Public Power Corporation (PPC) and are established in an area of 20km^2. The stability monitoring of the pits is performed using geotechnical sensors (inclinometers) as well as standard surveying methods.

The surveying measurements are critical to ensure continuity of monitoring especially after breakage of the inclinometers onto the slopes.

The implemented surveying monitoring regime refers to regular measurement of a number of prisms located at the top of each slope from selected base points. In addition, a further number of points that serve as control and one as a reference, because of their location in geologically stable grounds, are also monitored regularly. Having one total station located at a base point, measurements of angles and distances are taken initially to all control prisms and to the reference point, then to monitoring points and again to the reference point. The measurements are repeated from every 12h or few days depending on the deformation rate.

The paper gives in Section 2 a brief description of the lignite open pit mines of Megalopoli and describes in Section 3 the surveying data collection procedure implemented in the pit using simple instrumentation. The processing scheme is analysed and emphasis is placed on the mapping of all distance measurements to the atmospheric conditions of the first measurement taken, for the same baseline length. Although a simple approach, this provides significant improvement in the accuracy of point positioning without the need of expensive equipment infrastructure. The statistical analysis includes curve fitting evaluation from which deformation rates are estimated. In Section 4, results are given from a real scenario whereby the deformation rates, as estimated using the above surveying measurement scheme, indicated slope failure and appropriate preventive measures were taken in time to restrain collapse of the pit.

2. The Lignite Mines of Megalopoli

The Public Power Corporation (PPC) is the country’s largest electricity generator and currently the sole owner and distributor of electricity in Greece. It is the second largest lignite producer in the European Union and the fifth largest in the world as it mines approximately 70 million tons lignite per year.

The energy produced from lignite comprises 67.4% of the total energy that is produced by PPC in the interconnected system. Lignite is found in great abundance in Greece's subsoil. On the basis of Greece's total deposits and anticipated future rate of consumption, it is estimated that the domestic supply of lignite is enough to last for more than 50 years. It is therefore, critical to ensure the safety of the lignite mines whilst allowing reduction in the cost of mine production.

There are five open-cast lignite mines operated in the region of Northern Greece and in the Peloponnese region. The mining complex in the Peloponnese region, the Megalopoli Lignite Centre, produces approximately 15 million tons per year. Lignite from Megalopoli is used to supply power stations with units located within two kilometres from the mines, with a total installed capacity of 850 MW. The Megalopoli Lignite Centre comprises three open-cast mines, the Kyparissia mine which is located at the north of the complex, the Marathoussa mine which is located centrally and the Choremi mine which is at the south of the complex.

The accident ratio of the PPC mines decreased during 2004 with an occurrence ratio of 25%, which is below the corresponding levels of other European Union countries. The safety of the final cut slopes in the three mines is ensured by a monitoring system comprised by 27 inclinometers and a total of 57 monitoring points that are located at nine fronts with total length of 6km and monitored by conventional surveying techniques. Specifically, the Kyparissia mine uses 12 inclinometers and has 23 monitoring points, the Marathoussa mine uses 11 inclinometers and has 11 monitoring points, and the Choremi mine uses 4 inclinometers and has 23 monitoring points. In addition, there are a number of base stations whereby the surveying instrument is placed during data acquisition and a number of control points outside the excavation area which are used to check the stability of the base stations.

3. Low cost open pit monitoring system

Slope monitoring by surveying techniques in the open pit mines of Megalopoli is undertaken by a Leica TC1010 total station (range of 2.5km, quoted accuracy of 3mm+2ppm). The total cost of the monitoring system is in the order of 14K € at the time of writing (i.e. early 2006) which comprise the total station, 70 targets, a number of permanent base and reference pillars, associated hardware and software and one vehicle for transportation. The operational cost for one series of observations performed for nine monitoring areas is 140 € or 23 € per km. The cost for a robotic off-the-shelf monitoring system is in the order of 100K euros, for one instrument and associated software that can serve a monitoring front of about 4km.

The following sections describe the data collection scheme that is implemented for surface slope monitoring, the corrections applied to the measured distances in order to mitigate the errors due to the perturbed atmosphere of the mines and finally, the estimation of motion based on the corrected measurements.

3.1. Data collection

The data collection involves the measurement of the slope distance between the base station and each monitoring point. The rate of change of the slope distance gives the velocity of motion for the monitoring points. This information is used by the geologists of the Megalopoli Lignite Centre to perform risk analysis regarding possible slope failures. Given that the distance measurements are usually performed from one to four days and each distance measurement requires about 1min to be acquired, the accuracy of the time period is very high (i.e. 1:10000). In contrast to the time between measurements that can be considered without error, the actual measurements are affected by errors due to the atmospheric conditions of the mine environment (e.g. dust, high temperatures, atmospheric refraction).

Clearly, the mine environment affects significantly the atmospheric refraction in time, which in turn results in erroneous distance measurements. Measurements of the same distance may present variations at the level of few millimetres between different observation days, regardless of the temperature and pressure values at the observation point being noted and input into the software of the total station during each observation period. In order to minimise these variations, due to atmospheric refraction, in measurements of the same distance but acquired at different epochs, a data collection scheme is followed as described below:

Preliminary actions

- Installation of monitoring targets at positions on the pit walls indicated by the geologists.
- Installation of the reference target on a reference pillar, which is located behind the monitoring targets and at a distance of 100m or further if there is line of sight.
- Use of a base pillar located at stable ground and at the opposite slope.
- Installation of a small number of control targets behind the base pillar at distances of about 300m in order to eliminate their possible movement in case the base pillar exhibits motion.
- Position determination of the base and reference pillars from pillars of the national grid, which are located outside the mine area.

Initial measurements

- Forced centering of the total station at the base pillar.
- Measurement of external meteorological data (temperature at an accuracy of ±0.5ºC and pressure at an accuracy of ±1hPa) at the base pillar and input of these values at the software of the total station.
- Sighting to the reference target and measurement of angles (one period) and distance (3-4 values to obtain the mean value) and recording of time.
- Sighting to the first monitoring target and measurement of angles and distance.
- Sighting to the second monitoring target and measurement of angles and distance. The same procedure is repeated for all monitoring targets.
- When all monitoring targets have been sighted, then follows the sighting to the reference target and the measurement of angles and distance and recording of time.
- Sighting to all control targets, and measurement of angles and distance.

Monitoring measurements

- Repeat of all actions as described in initial measurements.

Figure 1 depicts schematically the typical installation of stations and points as used in the open pit mines of Megalopoli.

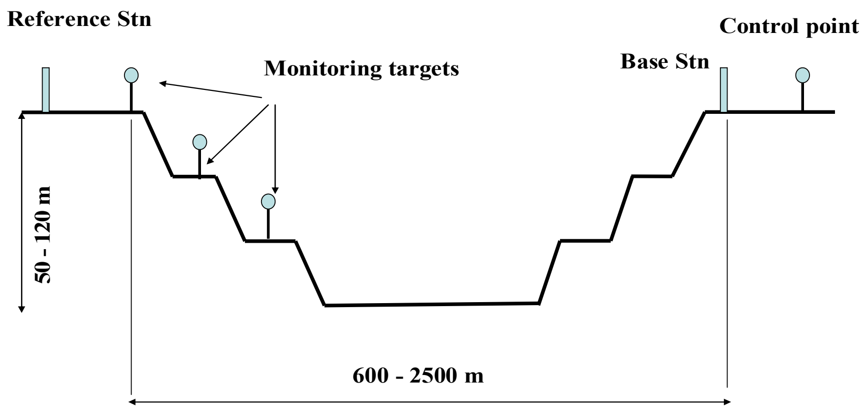

Fig. 1: Set-up for the field work

3.2. Correction due to atmospheric refraction

Atmospheric refraction can change dramatically throughout a day, which results to a bias in the displacement results at different times during the day. In slope stability monitoring it is commonly seen lines of sight that graze the side of an embankment, where the temperature gradient increases near the surface [1]. The temperature gradient changes very rapidly with sun exposure and areas that receive direct sunlight can produce gradients of several degrees per meter that fluctuate rapidly. This error if not corrected can easily lead to a misinterpretation of what is really happening to the deformable surface.

The basic idea for correcting the distance measurements at the lignite mines of Megalopoli is to reference all subsequent measurements to the initial atmospheric conditions of the first measurement. It is considered that the initial distance measurements of each baseline are "correct" at the specific atmospheric conditions. The accuracy of the initial measurements is considered equal to the manufacturer's quoted accuracy that is 3mm+2ppm for the specific instrument. This results in an accuracy of 7mm for typical measured baseline lengths of 2km.

The reference baseline is defined by the mean of the initial and last distance measurements to the reference target. In practice, however, the difference between the first and last measurements may differ up to few millimeters and sometimes the difference may reach few centimeters. Considering though, that the base and reference pillars are stable during the measurements, the aforementioned difference is attributed to the perturbed atmosphere of the mine environment. The standard practice is to estimate the refraction coefficient with reciprocal sights. However, it is simpler and faster to map (i.e. reduce) all monitoring measurements to the atmospheric conditions of the initial measurement.

This is performed by correcting the measured distances using mapping (i.e. reduction) coefficients which are given by equations (1) to (4). Below follows the definition of symbols required in the equations.

$D^{r}_{o'}$	first measurement to reference target (initial measurement)
$D^{r}_{o''}$	last measurement to reference target (initial measurement)
$D^{r}_{o\_mean}$	mean of the first and last measurements to reference target (initial measurement)
$D^{1}_{o'}$	measurement to monitoring target 1 (initial measurement)
$D^{2}_{o'}$	measurement to monitoring target 2, etc (initial measurement)
n	number of monitoring targets
$D^{c}_{1\_o}$	measurement to control target 1 (initial measurement)
$D^{r}_{m'}$	first measurement to reference target (monitoring measurement)
$D^{r}_{m''}$	last measurement to reference target (monitoring measurement)
D^{1}_{m}	measurement to monitoring target 1 (monitoring measurement)
D^{2}_{m}	measurement to monitoring target 2 (monitoring measurement)
D^{i}_{m}	measurement to monitoring target i (monitoring measurement)

The mapping coefficient for the first distance measurement to the reference target is:

$$a_{r'} = \frac{D^{r}_{o\_mean}}{D^{r}_{m'}} \tag{1}$$

The mapping coefficient of the last distance measurement to the reference target is:

$$a_{r''} = \frac{D^{r}_{o\_mean}}{D^{r}_{m''}} \tag{2}$$

The mapping coefficient of the distance measurement to the i-th monitoring target is:

$$a_{i} = a_{r'} - \frac{(a_{r'} - a_{r''}) \times i}{n+1} \tag{3}$$

The reduced slope distance measurement to the ith monitoring target (mapped to the atmospheric conditions of the initial measurement) is:

$$D^{i}_{reduced} = D^{i}_{m} \times a_{i} \tag{4}$$

In practice, the produced (from the raw distance measurements) quantities $D^{r}_{o\_mean}$, $D^{r}_{m'}$, $D^{r}_{m''}$, and $D^{i}_{m'}$, (where i = 1 to n) are used as input into a spreadsheet in order to calculate the coefficients $a_{r'}$, $a_{r''}$,. Furthermore, for each monitoring target the quantity $a_{i'}$, is computed which in turn is used to compute the reduced slope distance $D^{i}_{reduced}$ (Fig. 2).

It is seen in Fig. 2 how the reduction coefficient ai (as computed by equation 3) varies linearly in a set of eight distance measurements that were taken at a monitoring point in the open pit wall of the lignite mine. The measurements are considered to be obtained at equal times (i.e. 1min).

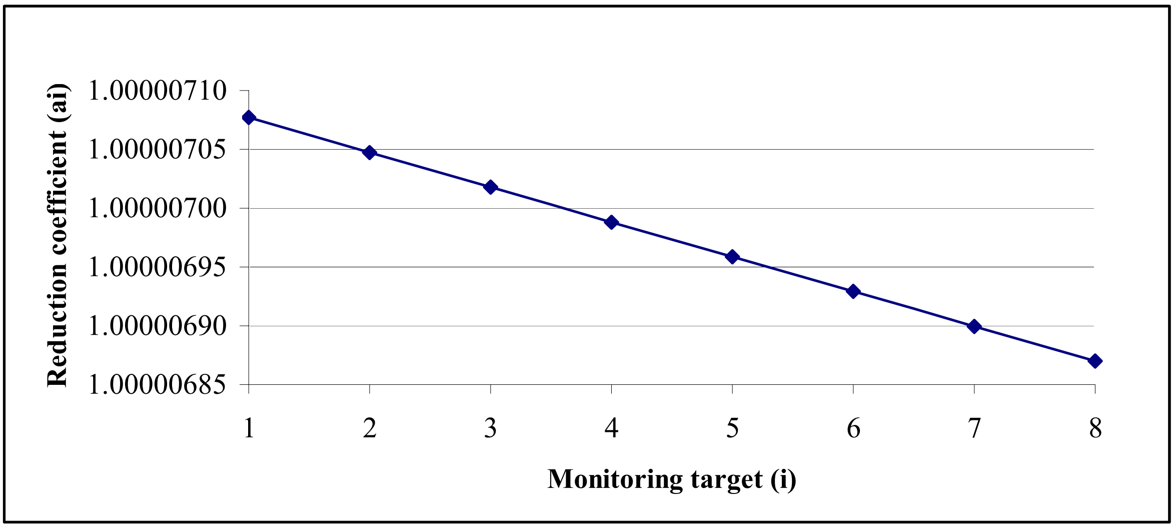

Fig. 2: Variation of the coefficient a_i in a set of measurements

3.3. Estimation of velocity

When the reduced distances are obtained, as discussed in section 3.2, then for each monitoring target "i" the daily values are used to estimate possible motion for the specific group of points by following simple procedures.

Initially, the difference $\delta D^{i}_{reduced}$ is formed between distance "i" of the initial measurement D^{1}_{o} and the current reduced distance $D^{i}_{reduced}$. Therefore, for each measurement there exists information about the difference $\delta D^{i}_{reduced}$ and the time of observation. This information is tabulated and is also graphed at the graph of "total movement" (Fig. 3a). The most recent three to five values are graphed into a different graph of the "last movement" (Fig. 3b). These values are used to perform a least squares best fit of a line, whereby its slope gives a good approximation of the velocity of the motion. When the slope of the best fit line is checked whether is positive or not along with the correlation coefficient, which preferably should have a value over 0.80, then the velocity value is estimated by the last three observations. Fig. 3a and Fig. 3b demonstrate the above from a typical example of a two-year time series of reduced distance observations and the way that the velocity of motion is estimated through the current observations in order to assess if there is possible motion that needs further attention. The observations are from the Kyparissia mine and refer to one monitoring target.

When the observation values present an unacceptable line fit but fit to a curved line with the concave looking upwards (i.e. indicating the acceleration of the motion), then these are further analysed in order to estimate the parameters of the parabolic function that better describe the specific values. The parabolic function is described by $\delta D = A + B \times (T - C)^2$, where A is the distance difference at the time of the initial measurement, B is a parameter that is related to the velocity of the motion, C is the observation epoch at which the parabolic motion has commenced, and T is the current time. The derivative of the parabolic function describes better the velocity of the motion of the monitoring target. All the aforementioned information is assessed by the geologists who decide upon remedial measures, such as suspend of slope cutting, filling of cut slope etc.

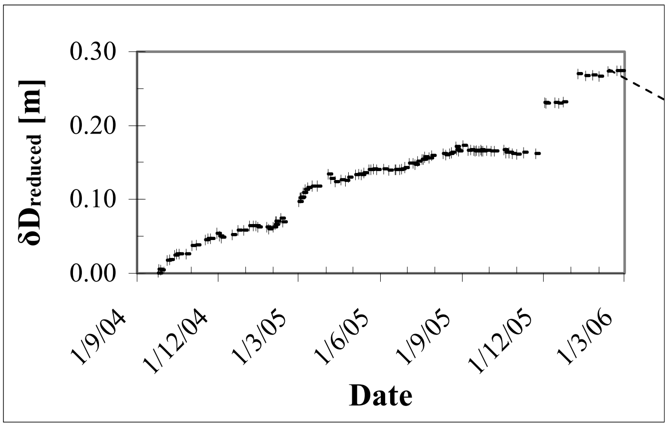

Fig. 3a: Time series of reduced distance differences $\delta D^i_{reduced}$

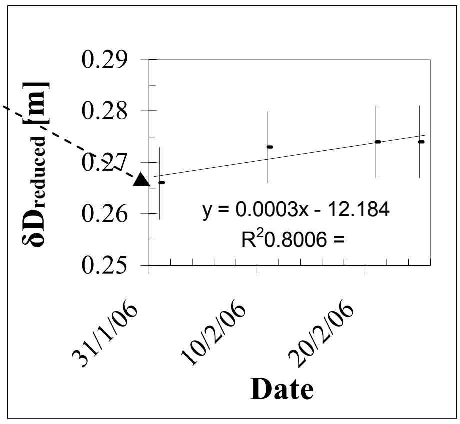

Fig. 3b: Velocity estimation from current observations

4. Case study

The methodology of data processing as described in the previous section enabled the successful detection of motion at the Choremi mine in summer 2004. Specifically, the geology section of the Megalopoli Lignite Centre advised the surveying section on July 15th, 2004 that a crack appeared at the east slope of the Choremi mine. The following day, one target was installed at the downhill side of the crack in order to monitor the motion.

The measurement taken at July 16th was considered as the reference observation. New measurements followed on the 21st, 25th, 27th, 29th, July and 1st August 2004 which gave velocities of 3.2 mm/day, 4.7 mm/day, 5.2 mm/day and 5.0 mm/day, respectively, when raw observations where used. Conversely, when the reduced distances were implemented, the respective estimated velocities were 3.2 mm/day, 5.8 mm/day, 5.3 mm/day, 5.6 mm/day and 6.0mm/day (Table 1). It was evident from the velocity values of even the first three observations, that there was occurring an accelerated motion.

The geologists decided to perform filling of the cut at the specific slope on 28th July, and the result of this action can bee seen on Fig. 4, whereby the accelerated motion was continuously reduced and finally became decelerated. Clearly, the slope failure was avoided and the remedial measures were successful.

Table 1 presents the raw and reduced distance measurements of the above days. It is seen that the best fit parabolic function gives statistically better results (smaller standard deviation and better correlation coefficient) when the reduced data are used up to the 7th measurement of 5th August. After that date, the motion cannot be correctly described by the same parabola because it becomes decelerated. The function that better describes the decelerating motion is of the form $\delta D = a \times e^{\frac{b}{T}}$ using raw measurements or logarithmic of the form $\delta D = a + b \ln T$ for reduced ones. Where a, b are parameters and T is time. It was statistically shown by examining the results that the reduced distance observations produced smaller standard deviation, better correlation coefficient and smoother residuals for both the accelerated and decelerated motions.

Date	**25.07.04**	**27.07.04**	**29.07.04**	**01.08.04**	**05.08.04**	**08.08.04**	**09.08.04**
Days	9	11	13	16	20	23	24
Measurements	3	4	5	6	7	8	9
Reduced measurements							
V [mm/sec]	5.8	5.3	5.6	6.0	6.5	6.0	5.8
A [m]	-0.006	-0.018	-0.022	-0.026	-0.031	-0.071	-0.096
B [m/days²]	20.E-05	11.3E-05	10.0E-05	9.26E-05	8.33E-05	4.91E-05	3.97E-05
C [days]	-5.5	-12.63	-14.82	-16.48	-19.052	-37.8	-48
Stand. Deviat. [m]	0.0000	0.0019	0.0013	0.0011	0.0010	0.0026	0.0026
Correl. Coeffic. R	1.0000	0.9985	0.9991	0.9995	0.9997	0.9983	0.9984
Raw measurements							
V [mm/sec]	4.7	5.2	5.0	6.4	7.0	6.6	6.3
A [m]	-0.015	-0.014	-0.029	-0.013	-0.017	-0.036	-0.054
B [m/days²]	1.17E-04	1.19E-04	7.77E-05	1.20E-04	1.07E-04	7.38E-05	5.80E-05
C [days]	-11.2	-10.9	-19.18	-10.40	-12.555	-21.773	-29.994
Stand. Deviat. [m]	0.0000	0.00004	0.0010	0.0014	0.0013	0.0026	0.0031
Correl. Coeffic. R	1.0000	1.0000	0.9994	0.9991	0.9994	0.9983	0.9979

Table 1: Computed parameters

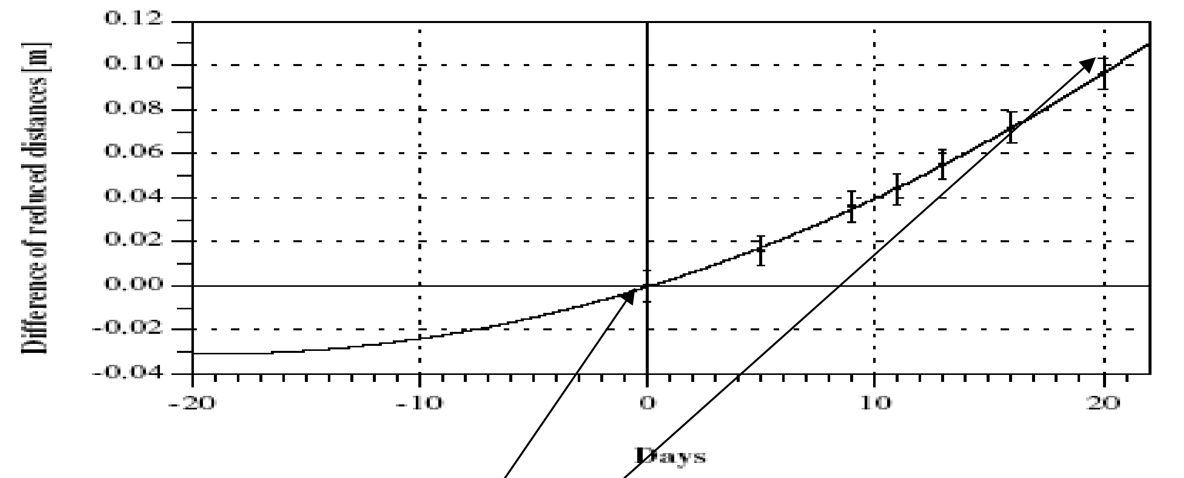

Fig. 4a: Initial distance observations (reduced) indicated accelerated motion

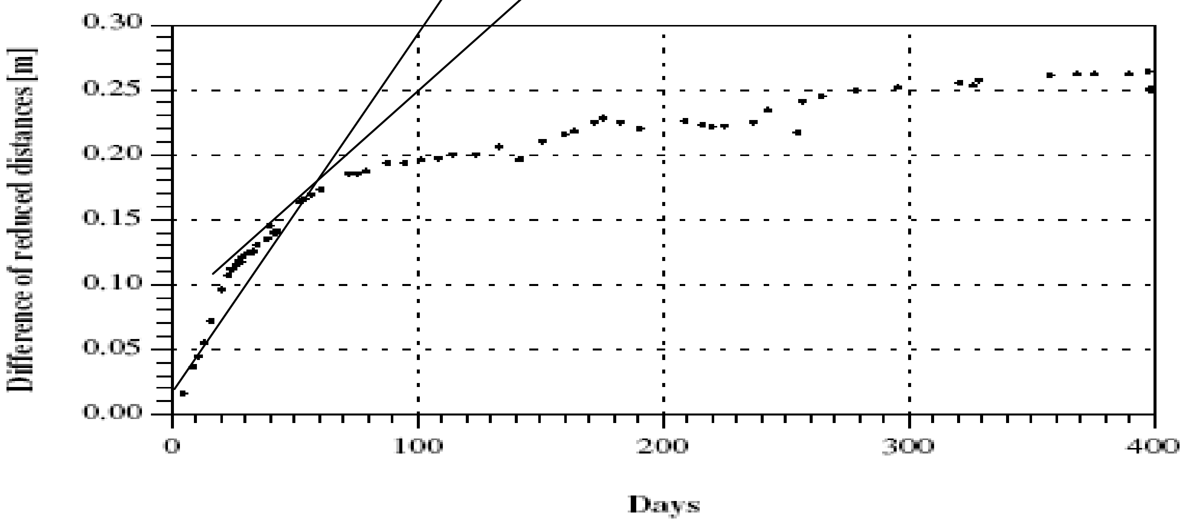

Fig. 4b: Time series of all observations

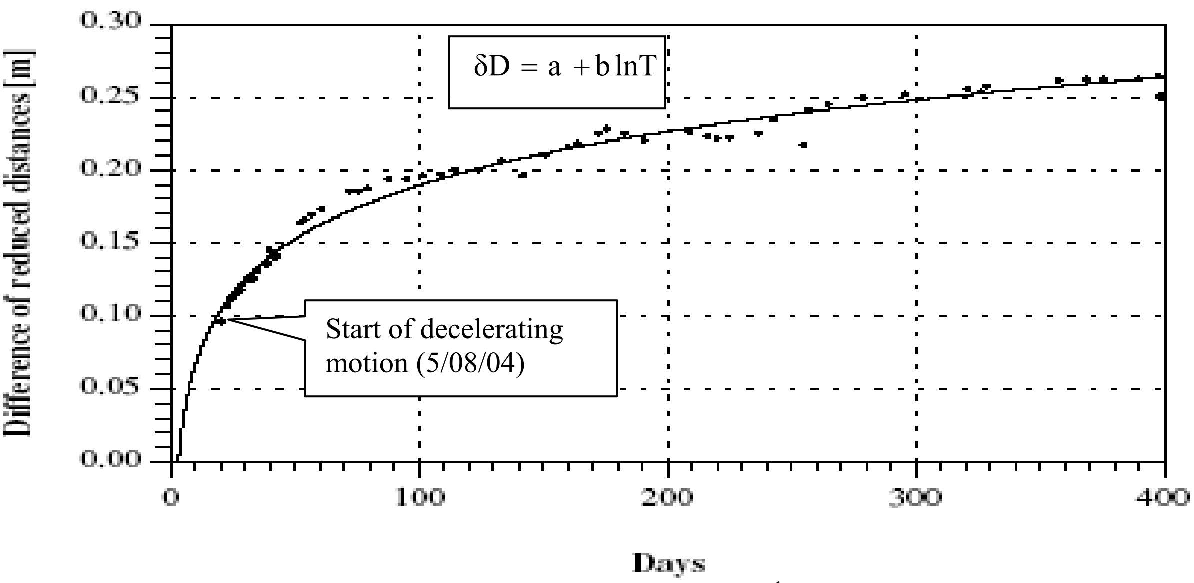

Fig. 4c: Motion became decelerated on 5th Aug. 2004

5. Concluding remarks

Fully automated monitoring systems for slope stability in open pit mines are desirable when continuous measurements are required but their cost is prohibitive for small scale deformation monitoring. The use of a low cost surveying system has shown to be capable of detecting motion of mine slopes in the lignite operations of Megalopoli in Greece, since the motions in the specific mines do not require continuous monitoring with measurements at a daily basis.

The observation scheme comprises measurements to a single reference station along with the monitoring points in order to map the distance measurements to the atmospheric conditions of the reference station, for the initial day. In this way, the distance measurements are corrected without the need of performing further measurements of reciprocal sights to compute refraction coefficients.

It was demonstrated that the system was capable in providing information about the motion of a moving slope as there is a statistical assessment of the results, and therefore, appropriate measures were taken in time to avoid failure of the slope. The use of a total station of greater range and GPS receivers for the control of base and reference pillars will facilitate the field work because the mine's future development requires monitoring points of greater distances. Future work will include further statistical testing to increase the monitoring scheme's reliability in false alarming.

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