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Integrating weather and geotechnical monitoring data for assessing the stability of large scale surface mining operations

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Abstract: The geotechnical challenges for safe slope design in large scale surface mining operations are enormous. Sometimes one degree of slope inclination can significantly reduce the overburden to ore ratio and therefore dramatically improve the economics of the operation, while large scale slope failures may have a significant impact on human lives. Furthermore, adverse weather conditions, such as high precipitation rates, may unfavorably affect the already delicate balance between operations and safety. Geotechnical, weather and production parameters should be systematically monitored and evaluated in order to safely operate such pits. Appropriate data management, processing and storage are critical to ensure timely and informed decisions.

This paper presents an integrated data management system which was developed over a number of years as well as the advantages through a specific application. The presented case study illustrates how the high production slopes of a mine that exceed depths of 100–120 m were successfully mined with an average displacement rate of 10–20 mm/day, approaching an almost slow to moderate landslide velocity. Monitoring data of the past four years are included in the database and can be analyzed to produce valuable results. Time-series data correlations of movements, precipitation records, etc. are evaluated and presented in this case study. The results can be used to successfully manage mine operations and ensure the safety of the mine and the workforce.

Keywords: slope stability; data management; relational database

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1 Introduction

Large surface coal mines that operate three shifts a day, 365 days a year, typically handle a considerable amount of geotechnical, mining, weather or other data on a daily basis. The open pit lignite mines in northern Greece operate in a similar pattern and have already reached depths of 150–200 m. Pertinent survey and geotechnical data including bench movements, pore pressures, inclinometer readings are gathered almost daily and are systematically used to assess slope stability. The amount of gathered data is enormous and a special management system is required in order to effectively store and evaluate the data. This paper presents a data management system which was used to manage such data.

This system can be operated in an internal network or via the internet and can collect data from a variety of sources, either in real-time or by manual or automatic import functions. The architecture of the system is based on a relational database with built-in data capture and analysis capabilities. This multi-user system ensures data integrity and allows for quick data access even for large or very large datasets.

The user can easily define fully parametric equations through a graphical user-friendly interface in order to calculate new variables, such as rates of movement, displacement vectors, etc. The database system can identify missing information, duplicate entries, records which exceed warning and alarm limits and the user can easily export data in reports, tables and charts. The locations of the monitoring points can also be displayed in multiple map environments such as Google maps and AutoCAD layouts. The user can select single or multiple points on the maps and present the monitoring information via tables or graphs.

This database system was successfully utilized at a surface lignite mine in northern Greece to allow safe mining operations on moving slopes. These production slopes are located in a deep seated moving mass. Mining is performed using large (and expensive) bucket wheel excavators (feeding onto bench conveyor belts) which continuously mine the overburden, interburden and the lignite. This is a continuous mining operation and equipment relocation is a slow process that takes place after careful planning. Therefore, it is not easy to suddenly remove all equipment from a specific bench or benches. To ensure safe operations, a systematic monitoring schedule was implemented. The monitoring process allows for a quick and accurate prediction of the behavior of the slopes and provides input for critical decisions such as slope inclination modification, potential halting of operations and/or potential slope evacuation.

2 Monitoring requirements and system architecture

Survey target points were installed on almost every bench of the mined slopes and at different locations on each bench. The target points were surveyed with a robotic total station with an accuracy 0.5cc from two benchmark control stations, located at the opposite side of the slopes. The benchmark stations were also monitored with GPS in order to verify their stationary conditions. The target points were usually surveyed with intervals of 1 to 3 days. In situations where the movement rate appeared to increase, the survey intervals could be modified to 2 or 3 measurements per day. This monitoring schedule was combined with 60 survey targets and the quick evaluation needed can be a tedious task. In order to accommodate the amount of data generated, which can vary between 2000–3000 measurements per year, a data management system was designed and implemented.

The database system allows for user defined hierarchical grouping of data sets in multiple levels. For example, a project group can include multiple projects (*i.e.* mines or mining areas), a project can include multiple sectors (*i.e.* north slopes, south slopes) and a sector can include multiple sensor groups (*i.e.* instruments on bench A1). Finally, each sensor group includes multiple sensors or instruments and the associated measurements.

Figure 1 presents a simplified form of the database architecture schema.

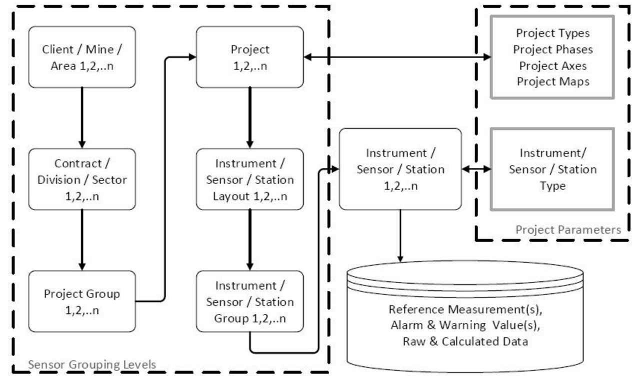

Figure 1: Schematic representation of the database structure

The user can define any instrument or sensor type by defining the measured and/or calculated variables for each such type. Each sensor type is implicitly defined as a time-series data handling sensor. For example, a single variable sensor would be used in the case of monitoring water elevation at a specific location, while a multiple variable sensor would be used in the case of a survey target "sensor". In addition, multiple calculated variables can be added to each sensor such as displacement vectors, displacement rates, etc. To accomplish the latter, a custom equation editor is built into the software as well as the capability to perform calculations based on measurement values or difference values. Instruments or sensors are then generated based on a corresponding type, *i.e.* multiple survey "sensors" are generated based on the same sensor type.

Data for each sensor or instrument include constants such as installation coordinates and installation date, instrument status, grouping level, etc. The database stores all raw data for different dates and times. The user can select to reject or exclude data points from the analysis, but all raw data is still kept in storage. Measurements can be imported either through an Excel file, other text files or even manually.

After dates and measurements have been imported, the user needs to set or reset the reference measurements for each instrument. Multiple reference measurements are allowed. The calculation process is then initiated through which all calculated variables are calculated and stored. This process can be applied either to a single instrument, an instrument group or even a higher level grouping level. Following that, the system is able to identify when warning or alarm limits have been exceeded for either a directly measured or a calculated variable.

After completion of the calculation phase, all raw data or calculated variables can be viewed through time series or polar charts. Any type of variable combination can be plotted in these charts. The database can generate predefined reports that include raw data and calculated variables in tabular or charted format. Statistical information for each instrument group or project can be easily retrieved and includes the total number of instruments and measurement records, the number of reference dates etc. Finally, all instrument / sensor locations defined within a project can be displayed on Google maps or AutoCAD files based on their coordinates. Furthermore, the user can select multiple points for display on the maps and then chart selected variables per instrument by just clicking one each or multiple instruments.

3 Monitoring of the mine slopes and data evaluation procedure

Significant displacements have been measured in the south and southwest production slopes of the mavropigi lignite mine in northern Greece. The lignite produced is very important for the Greek economy and production cannot be suspended. The factors causing such movements are attributed to the complex geology and tectonics of the region, the process of the mining operations, environmental conditions or the geotechnical parameters of the ground [1–3].

Mine management decided that as long as the reasons for the slope instability are known and the movement can be monitored and critically assessed, mining operations could continue even on (slowly) moving slopes. However, it was important to determine the type of movement that pertained to the moving mass. If the moving mass exhibits a regressive type of movement in which at different time intervals, movement accelerates and then decelerates, the mine operation can continue with the implementation of a monitoring system [1]. The critical parameters that needed constant evaluation were the change of movement rate (velocity), the local precipitation amount, and the vector displacements for all survey targets installed on the slopes under monitoring. Based on the critical parameters, the inverse rate of movement versus time is a very useful indicator of forecasting potential slope failure [4].

The aforementioned database system was used to store and evaluate all the survey monitoring data and correlate them with the precipitation values gathered from a nearby weather station. Sixty survey targets have been included in the database with more than 8500 measurement records that have been recorded since 2012. The coordinates and the installation date for each monitoring survey target were imported into the system.

The survey data is generated in cartesian coordinates (X, Y, Z) in the EGSA87 geodetic system. These data are uploaded in the database system and all other calculated variables such as rate, cumulative vector displacement, etc., are then calculated. Measurement records of different survey targets were grouped in three groups corresponding to three mine areas: the area of the ‘A’ conveyor belts on the south slopes of the mine, the area of the ‘B’ conveyor belts on the southwest slopes and the area of a nearby fault. Figure 2 presents a google maps image of the mine slopes where the location of the survey targets are superimposed. This image was generated from within the database system.

Figure 2: Location of sensors on Google maps.

The systematic evaluation of these parameters was crucial for the safe mining operation. The displacement data, especially the rate of movement, were correlated with precipitation data in order to generate warning and alarm limits for precipitation related movements.

4 Monitoring results

Displacement data for the south and southwest slopes of Mavropigi mine were available from the beginning of 2012 until the end of August 2015. All data were stored in the database and critically evaluated. Due to space limita-

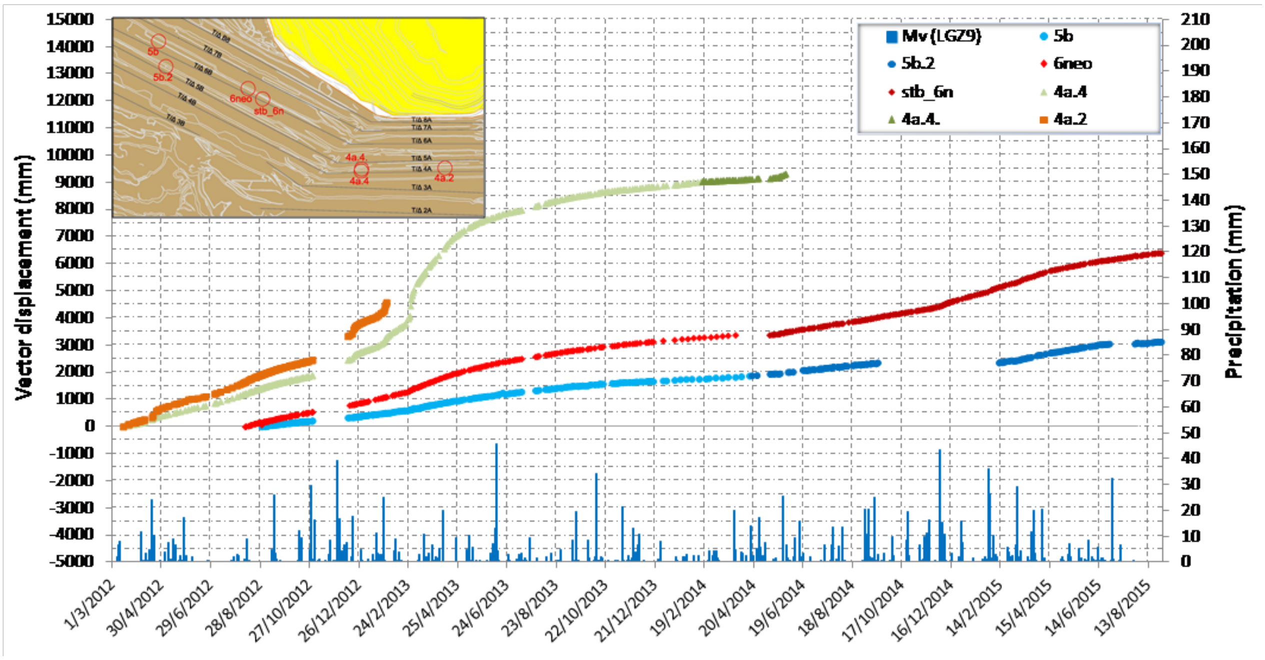

Figure 3: Vector displacement of survey targets in the area of the "A" and "B" Conveyors.

tions, all data and analysis cannot be presented here, so only some characteristic patterns will be shown. In addition, the long term evaluation of such monitoring data presents difficulties due to the nature of the continuous mine operation. Survey targets are many times destroyed or moved due to the mining. In most (but not all) cases such targets were reinstalled but at different locations and elevations. The difference in distance between the initial and the replacement survey target can be of the order of 20–100 m. Therefore, measurement continuation is disrupted and many times synthetic displacement and rate graphs need to be prepared. The program allows for multiple reference points, so continuous graphs and analysis can be generated, but this inherently assumes that the replacement "sensor" will be close to the original one.

Figure 3 presents the cumulative displacement for the south slopes (area A of the mine; targets 4a.2, 4a4, 4a.4.) and the southwest slopes (area B of the mine; targets 5b, 5b.2, 6neo, stb_6n) from March 2012 to August 2015. The regressive type of movement can be easily observed. for example, between February 2013 and June 2013, the movement of target 4a.4 (light green color in the graph) is accelerating, and from June 2013 to February 2014 the movement is decelerating. The deceleration can be attributed to a combination of lower precipitation as well as a modification of the excavated general slope of the mine. This figure is crucial in the assessment that the mine operation can safely continue on moving slopes. Contingency measures, such as changing the profile of the slope by excavating masses at the top part of the slope (unloading), are implemented when the general rate of movement appears to increase. This graph was used for the long term evaluation and planning of the mine operation. The rate change (velocity) diagram in combination with precipitation data was used for short term evaluations.

Figure 4 shows velocity versus time as well as the daily water precipitation. It is evident that when significant (above 15–20 mm/day) precipitation occurs, the displacement rate (velocity) increases abruptly. In addition, it is observed that increased displacements occur after a time lag of 1-3 days following a precipitation event. The rate of movement drops to typical values after around five days, following maximum rates recorded after a significant precipitation event and if no other significant precipitation occurs during that time. This information is of critical importance for assessing the safety of the operation. It must be noted that the rate of movement is very much depended on the general slope profile. Therefore, typical rate values cannot be estimated; only relative values at different time frames are useful for interpretation.

Figure 5 presents vector displacements at the south and southwest slopes. The red arrows are scaled by a factor 200 for better visibility. It is observed that higher cumulative displacement is measured at the center part of the slopes in relationship to the western part. The vector magnitudes and directions indicate that a form of translational – rotational movement is taking place following the greater fault area as delineated with the magenta line.

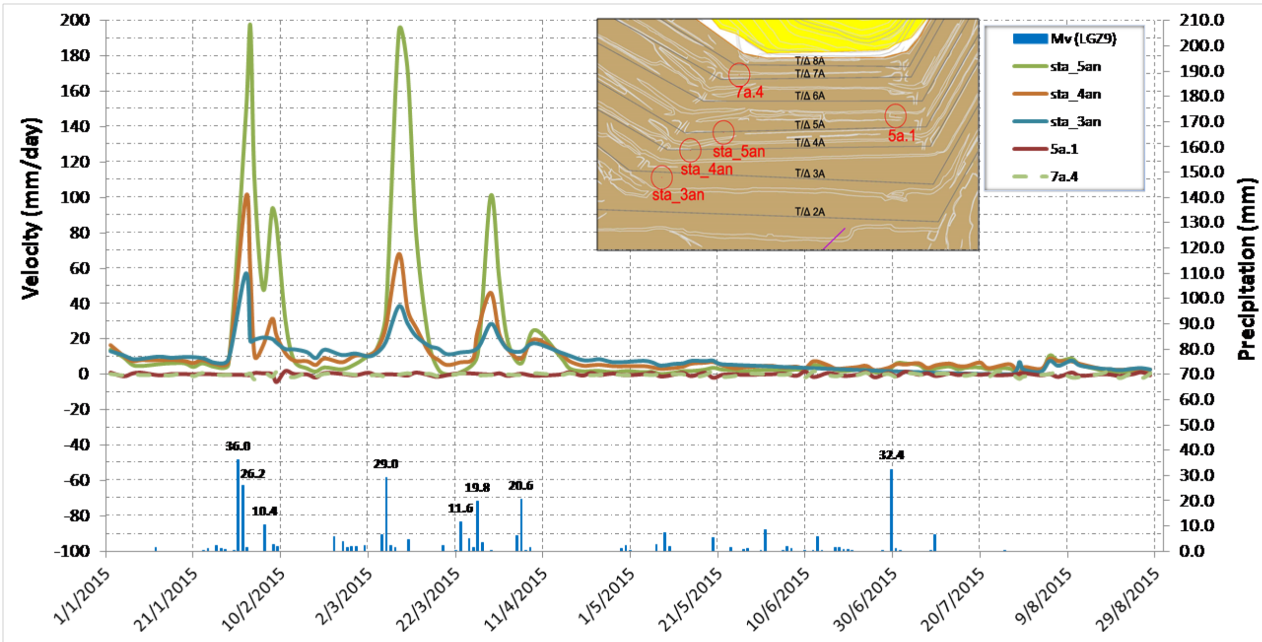

Figure 4: Velocity of survey targets in the area of the “A” Conveyors.

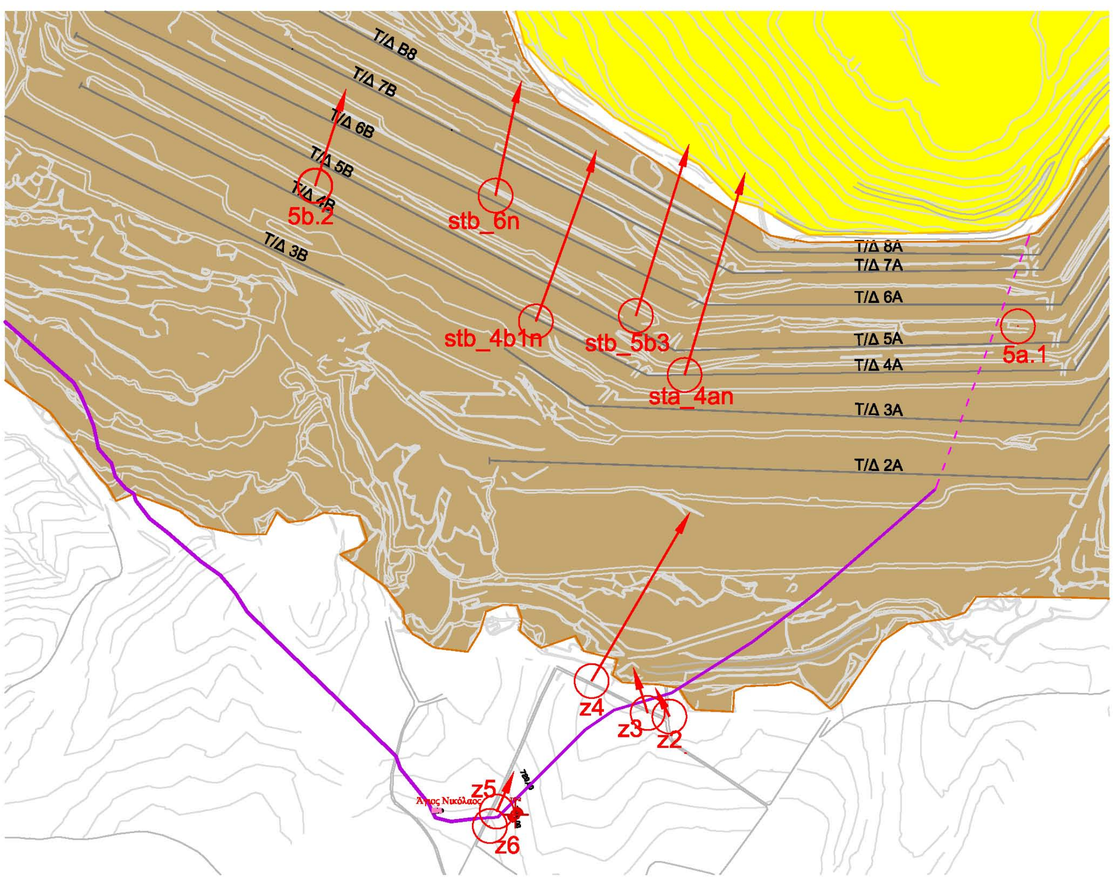

Figure 5: Location of survey targets and displacement vectors.

The vector displacement is very helpful when used in correlation with geological and geotechnical data such as inclinometer measurements in order to assess and interpret the movement mechanisms.

5 Discussion and conclusions

A database management system is presented which is utilized to store and evaluate large amount of monitoring data of slope movements at a surface lignite mine in northern Greece. Using a database system is of paramount importance for the quick evaluation of numerous parameters in order to assess the safety of mine operations. Due to the large amount of data generated from the monitoring schedule it is too time consuming to perform manual calculations in Excel spreadsheets. Finally the ability to store and retrieve data for different time periods and the ease of creating correlations of multiple data streams at different time intervals, significantly increases productivity and enables quick decision making for mine operations.

The case study presented demonstrates the usefulness of a data management system in everyday mine operations and the way it can be used to safely operate a large mine operation, even on moving slopes. The most important outcome achieved by the application of this database system is that mine operations can continue safely, even in slopes that generate movements of 1–2 m per year. In addition, recorded data show that operations are in progress even with daily rates of movement in the order of 100 mm/day. For this particular mine, rates as large as 200 mm/day have been recorded without collapse. Mine operations have been temporarily suspended when high rates above 100 mm/day had been measured. Mine operation is only possible due to the regressive type of slope movement and the extended monitoring schedule which significantly contributed to the determination of the overall slope behavior. The correlation with precipitation data indicating that the high rates decrease to normal values after five days assists significantly to evaluate the suspension period in relationship to precipitation. Furthermore, excavation schedules can be adjusted based on the displacement values and displacement rate measured at the slopes in order to try to reduce movements to average values.

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