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THE VELENJE COAL MINE'S SPATIAL MONITORING OF SURFACE AND STRUCTURE MOVEMENTS

SPREMLJANJE PREMIKOV POVRŠINE IN OBJEKTOV NA OBMOČJU PREMOGOVNIKA VELENJE

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Keywords: geodetic monitoring, observation networks, surface movements, Velenje Coal Mine

Abstract

The Velenje Coal Mine's (VCM) system of surface observation is complex and can be classified as an extended geodetic monitoring system. In addition to the standard geodetic techniques (triangulation, trilateration, levelling, GNSS), it also includes more modern methods such as aerophotogrammetry, terrestrial laser scanning and an automatic Real-Time GNSS Deformation Monitoring System. By using the Real-Time GNSS Deformation Monitoring System, we are able to monitor not only the potential impact of mining on the power plant facilities but also the impact of the newly constructed power generating facility, Unit 6, and the combined effects on existing facilities. With an extended geodetic monitoring system, the surface movements and deformations on over 300 measurement points in the Šalek Valley are observed. Furthermore, with sonar measurements, we are determining the Šalek lakes' bottom surface and performing observations of structure movements and deformations. The extended VCM geodetic monitoring system is constantly being expanded and upgraded with new measurements and the latest equipment.

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Povzetek

Premogovnik Velenje d.d. je za potrebe spremljanja in zagotavljanja varnosti na območju pridobivalnega prostora in širše vzpostavil takšen sistem opazovanja površja, da ga lahko klasificiramo kot razširjen geodetski monitoring sistem. Ta zajema poleg standardnih geodetskih tehnik (triangulacija, trilateracija, nivelman, GNSS) tudi modernejše metode, med katere sodijo aerofotogrametrija, terestrično lasersko skeniranje in samodejni GNSS sistem za spremljanje pomikov in deformacij v realnem času. S slednjim ne samo da preventivno spremljamo potencialni vpliv rudarjenja na objekte Termoelektrarne Šoštanj (TEŠ), ampak tudi vpliv novogradnje Bloka 6 TEŠ ter kombinirane vplive na obstoječe objekte. Z razširjenim geodetskim monitoring sistemom spremljamo premike in deformacije površine na preko 300 merskih točkah v Šaleški dolini, izvajamo sonarske meritve za določitev dna šaleških jezer ter premike in deformacije objektov (npr. Klasirnica PV in TEŠ). Razširjen geodetski monitoring Premogovnika Velenje nenehno razširjamo z novimi meritvami ter ga nadgrajujemo z najsodobnejšo opremo.

1 INTRODUCTION

The Velenje Coal Mine (Premogovnik Velenje d.d.), the largest Slovenian coal mine, with an annual production of four million tonnes of coal, sends nearly all of the extracted coal to the Šoštanj Thermal Power Plant (Termoelektrarna Šoštanj) for the production of electricity. The technology of coal extraction is carried out with the Velenje Mining Method [1], resulting in subsidence of the overlying strata and the formation of surface depressions. Figure 1 shows the Šalek Valley with the mine roadways of the Velenje Coal Mine in black. Since the security of significant energy installations, such as thermal power plants and coal mines, and their impact on the environment are vital for the efficient operation and associated good public opinion, movements of the surface and deformations of structures have been monitored under the auspices of the technical services of the Velenje Coal Mine.

Figure 1: *A broader area of the Velenje Coal Mine showing the mine roadways (black) and points of observation networks on the surface (red).*

Monitoring the movement of the surface covers measurements of observation networks, dams between lakes and the bottoms of lakes; moreover, monitoring of nearby industrial and residential buildings is also carried out. Today, it can be said that the system for monitoring the surface and installations, and for further forecasting movements of the terrain with the help of computer models can be classified as an expanded geodetic monitoring system.

2 METHODS OF MONITORING MOVEMENTS AND DEFORMATIONS

As a part of monitoring the movements and deformations on a wider area of the Velenje Coal Mine, we carry out measurements on the surface and individual buildings (Figure 2).

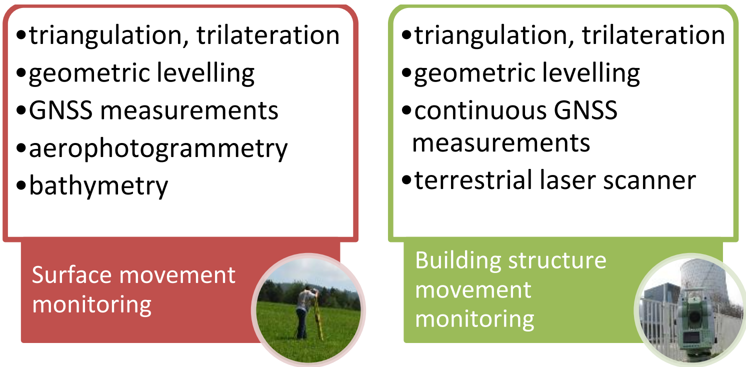

Figure 2: *The methods of monitoring movements and deformations on the area of The Velenje Coal Mine.*

2.1 Monitoring of the surface

2.1.1 Monitoring of the surface

The impact of excavation on the surface is reflected in the changes in the terrain with the formation of depressions on the surface shortly after starting excavations, reaching 90% of its final value about three months after the end of excavations. Since many excavation panels are active at the same time in the Velenje Coal Mine and the excavation of one begins immediately after the excavation of another ends, it is difficult to discuss the impact of one particular excavation panel on the surface. With the measurements of the observed points on the surface, we monitor the development of the movements due to more excavation panels on a particular area on the surface. Because we carry out the measurements of the field movements in the spring, we discuss the impact of the excavations that have been under excavation the year before the measurements.

We monitor over 300 observation points on the surface on the wider area of the Velenje Coal Mine, which we group into observation networks (Table 1). To determine the coordinates of the base points of each observation network, which are an integral part of the main network of the Velenje Coal Mine, the so-called Small Geodynamic Network of the Velenje Coal Mine, we carry

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out measurements with the GNSS (Global Navigation Satellite System) method of surveying. We carry out the observation of points of most of the observation networks with a classic terrestrial method of measurement, whose results are three-dimensional coordinates (Y, X, H) in the National Gauss-Krüger coordinate system. For a more accurate determination of the heights of the observation points of certain networks, we also use the method of geometric levelling. The measurements of the observation networks are generally carried out at least once a year; in specific cases, they are carried out more often, as much as many times per month (Table 1).

Table 1: *The observation networks of the Velenje Coal Mine with the number of measured points, type and frequency of measurement.*

Name of network	***Number of points***	***Type of measurement***	***Frequency [annually]***
MGM PV	18	GNSS	1
Glavna PV	145	T + N	1
Pesje	25	T + N	1
Škale	21	T + N	1
Gaberke	29	GNSS	1
Ravne	12	GNSS	1
Videčnik	25	T + N	12
Turn	9	T + N	4
Pocajt	6	T + N	12
Kompan	4	T + N	4
Blatnik	2	N	6
TEŠ	6	T + N	12
NOP II	7	GNSS	4
NOP II	12	T + N	12

Legend:

T – terrestrial measurement method N – method of geometric levelling

2.1.2 Aerophotogrammetry

Within the pilot project, we also carried out aerophotogrammetry of the surface directly over the excavation panel G2C in the Preloge mine (Figure 3). Aerophotogrammetry is a measurement technique for recording the earth's surface from the air and, on the basis of the acquired imagery, the elaboration of plans and making of a digital elevation model of the terrain, [2]. The excavation of the G2C panel started on 16 May 2010 and finished on 31 January 2011. The excavation was horizontal; the average height of the excavation panel was 5.2m [3]. Aerophotogrammetry was carried out in three periods: in April and September of 2010, and in April of 2011. The photogrammetric measurement was made with an automatic correlation of

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the heights in a raster of 5×5 m. The basis for geo-locating the photogrammetric measurements was approximately 10 points that were marked on the field and measured with the Differential GNSS method. Apart from that, a larger number of points were also measured on the field, which served for improving the photogrammetric measurements and controlling the results.

Figure 3: *The locations of the excavation panel G2C in the Preloge mine of The Velenje Coal Mine.*

2.1.3 Bathymetric measurement of lakes

In the Šalek Valley, there are three subsidence lakes, which are a result of coal extraction (Figure 1). Measuring the lakes is intended for observation and tracking the impact of the excavations to the surface and the transformation of the terrain; it is carried out once a year. In PV Invest d.o.o., Reason NaviSound 110 sonar has been used for measuring the depths since 2010, as it enables connection to a computer and GNSS device; the results of the measurements are points with given Y, X, Z coordinates and the depth. The procedure for measuring lakes is as follows: the lakes are measured in a square net with the sonar and the GNSS determination of the location in real time (RTK method); the size of a cell is approximately 25 metres; measurements are made every 5 metres (Y, X, H, depth). At the same time, measurements of the temperature of the water at different depths are performed. What follows is the processing of the depth data, where the impact of the water temperature on the speed of sound transmission in the water is taken into consideration. Furthermore, a model of the lakebed is made from the corrected measurements. Based on models of the lakebed from each year, subsidence areas under the lakes can be seen.

2.1 Monitoring building structures

The subsidence of the surface consequently endanger building structures on the impacted area of excavations, with hairline cracks first appearing, followed by moderate structural damage, and possibly finishing with a collapse. Within the boundaries of the extraction area, there is a

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small number of building on which the monitoring of movements and deformations is carried out if necessary. The decision to do so depends on both the expected movements of the surface near the building, and the actual state, which is obtained via continuous measurements of the observation networks.

In PV Invest d.o.o., movements and deformations of buildings are monitored using the classic method of land surveying, but also with the use of terrestrial laser scanning (TLS), and with the advanced automatic continuous GNSS monitoring system for displacements and deformations in real-time, which consist of the most advanced measuring instruments and software specially designed for deformation monitoring.

2.2.1 Monitoring building structures with the methods of classic and GNSS measurement

Monitoring of the movement of buildings is done with the methods of classic land survey, i.e. with terrestrial surveying method and the method of geometric levelling. Relative GNSS surveying methods with post-processing of observations that provide maximum precision in position determination may also be used. Such measurements are carried out on buildings that are located near areas where movement has already detected, or, in the vicinity of expected movement (Figure 4).

Figure 4: *Monitoring the movements on a building with: the method of geometric levelling (left), the static GNSS measurement (middle), the use of a 3D terrestrial laser scanner (right).*

On a stable area in the vicinity of the building, a basic network is set up. The most suitable method is to carry out the measurements with the terrestrial method through individual points of the basic network. When this cannot be done, it must be ensured that the 'free-station' locations for observing buildings through linear and angular measurements are connected to at least three points from the appropriate network. The measurements are conducted in many sets, based on which the coordinates of the 'free-station' locations are individually assigned each time. From the 'free-station' locations, the characteristic points that are to be built into the building, also in many sets, are then observed.

As part of optimizing the transport routes in the Coal Mine Velenje, a new 505-meter deep shaft for the transport of coal to the surface is being made. Cave surveying services, in the construction of the shaft NOP II, cover, in the first phase, setting up the basic initial observation network of the shaft, through which the movement and deformation areas of the shaft and the

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shaft itself during its construction are monitored. Regardless of the building to be monitored, the starting observation network must be designed so that it is possible to carry out control measurements of its stability, and that it is possible to determine the size of the movement of each observed point in the network at any time of the measurements, [4]. Points of the initial observation network are placed around the construction site of the shaft so that the visibility is provided between them (Figure 5). The location of pillar points has been predetermined on the basis of the position of buildings on the construction site and the photo of the broader state around the building (landfill). The final locations of points are thus determined on the basis of the control visibility between points on the field after the finished construction of the main buildings on the construction site of the NOP II shaft.

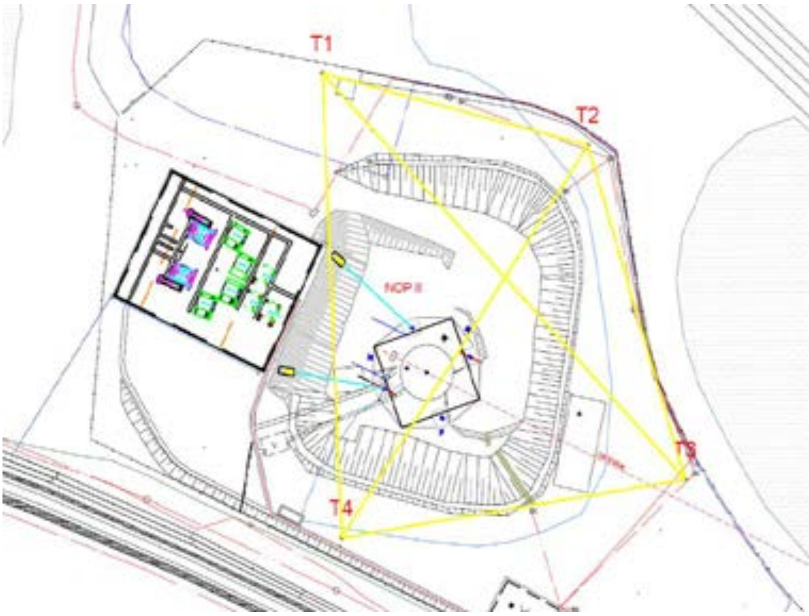

Figure 5: *The situation in the area of the NOP II shaft with the observation pillars – points of the initial NOP II network.*

The basic local observation network of the NOP II shaft is made up of four control points (T1, T2, T3 and T4), which are located in the NOP II shaft area (Figure 5) and three reference points, which are part of the MGM PV. Observations in the initial observation network are carried out, [4]:

- Once a month terrestrially in at least three sets with the electronic Leica TPS 1201+ tachymeter. This means that the horizontal and vertical movements in the network are determined with the electronic tachymeter by measuring the horizontal direction, vertical angles and inclined lengths. Furthermore, the vertical movements are determined with a more precise geometric levelling. Angular observations are carried out via the method of sets. In this way, the internal stability and non-deformability of the basic initial network NOP II is controlled.
- Once every three months, the initial observation network is attached to the basic PV grid. These measurements are carried out with a static GNSS measurement with the

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use of Leica GPS1200+ GPS receivers. In this way, the movements of the basic initial network of the NOP II shaft and the stability of the external network are determined.

2.2.2 Monitoring building structures using the terrestrial laser scanner (TLS)

Scanning with a terrestrial laser scanner enables the creation of a highly precise surface network of an area or building, which is extremely important for the perception of spatial changes between instances of measurement. The company PV Invest d.o.o., in co-operation with the Faculty of Natural Sciences and Engineering of the University of Ljubljana, has conducted a scanning of the sorting plant building of the Velenje Coal Mine in two periods separated by nine months, [5]. The measurement was carried out with the Leica Scanstation 3D terrestrial laser scanner (Figure 4, right), while the processing and modelling were carried out with the Cyclone and AutoCad programs. The final interpretation was made in the program MS Excel. In total, 9,326,790 points were captured and, after filtering clutter and eliminating the irrelevant points, there were 4,986,600 points used at the end. The registration and geo-referencing was based on five connection points whose coordinates were determined with classic (TPS) measurements.

2.2.3 Automatic continuous GNSS system

As part of the preparatory work and hereinafter the construction of TEŠ Unit 6, PV Invest d.o.o. conducts measurements of stability of the existing building, as well as calculations of movement and the preciseness of the movement. For this purpose, a measurement network of the automatic uninterrupted GNSS monitoring has been established, which consists of three GNSS observation points (GMX N, GMX S in GMX E) that are located at the periphery of the top of the cooling tower of Unit 4, two observation points with a tilt sensor (NIVEL n and NIVEL s) that are located above the ground at the periphery of the top of the cooling tower of Unit 4, a reference (stable) GNSS point (GRS O) is placed in the facility of the pumping station of TEŠ on the Paka River, next to it is also a point-with-a-tilt sensor (GRS o) (Figure 6). All points are directly linked to the central computer where observations of all the sensors are collected. The central computer can be accessed remotely via the internet, enabling examination of the measurements whenever and wherever desired. A detailed schematic is shown in [6]. The software is configured for automatic conversion of three basis vectors: the GRSO-GMXN, GRSO-GMXS and GRSO-GMXE. Automatic parameters that are post-processed by GNSS and a 15° angle are chosen. For the purpose of further analysis of achievable precision in dependence of the length of measurement time, products were created every: 10 min, 30 min, 1 h (for experimental purposes) and every 3 h, 6 h, 12 h, 24 h. To determine the movements, 24-hour intervals of measurement were selected, as the expected movements are slow and the highest accuracy was achieved (order of mm).

Figure 6: *The position of the measuring points of the automatic uninterrupted GNSS monitoring in TEŠ.*

3 RESULTS

3.1 Monitoring of the surface

3.1.1 Observation networks

Based on the processed point measurements of observation networks from different periods of measurement, the movements are calculated. The result of the horizontal and vertical movements of the observed points is made into a table and a graphical display according to individual years; the maps of the isolines of the movements are also plotted (Figure 7).

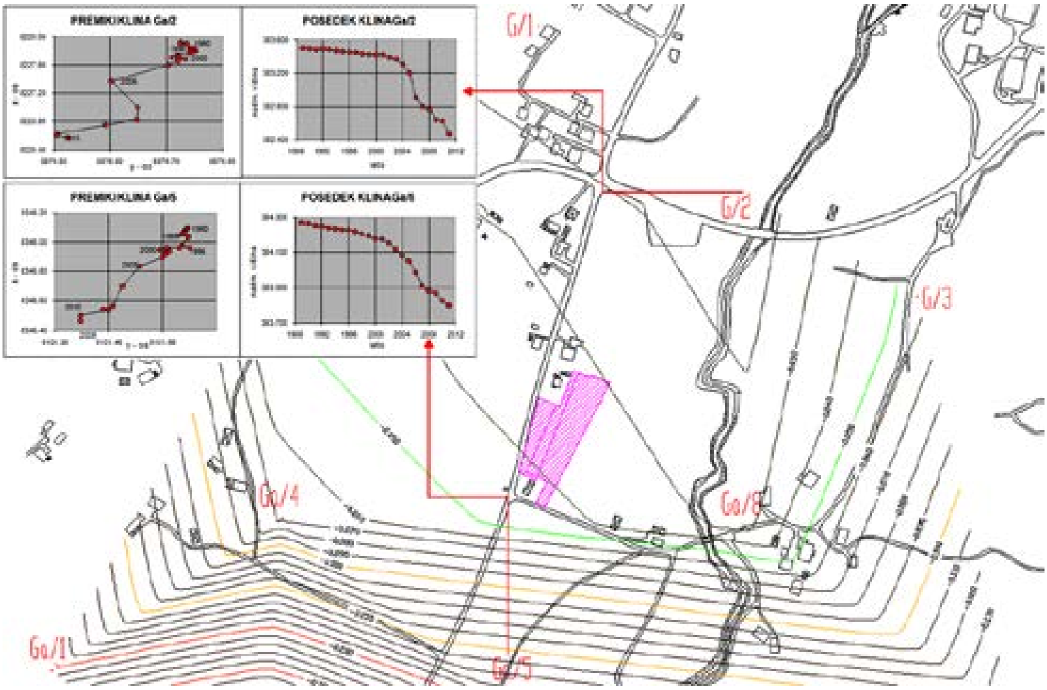

Figure 7: *A map of the vertical movement isolines made based on the results of measurements in two periods of the observed points, and a graphical display of the individual points' movements.*

3.1.2 Aerophotogrammetry

The final results of the calculated subsidence based on the aerophotogrammetry from measurements of three periods are shown in Figure 8. The results reflect the expected maximum settlements in the area of the excavation panel, which are decreasing in the directions away from the excavation panel. The results are consistent with the anticipated chronology of the terrain subsidence; the terrain subsidence, which refer to the changes in April 2010–September 2010 (the excavation is active for about five months), are smaller than the terrain changes in the period of April 2010–April 2011 (the excavation is complete). Detailed results are shown in [7].

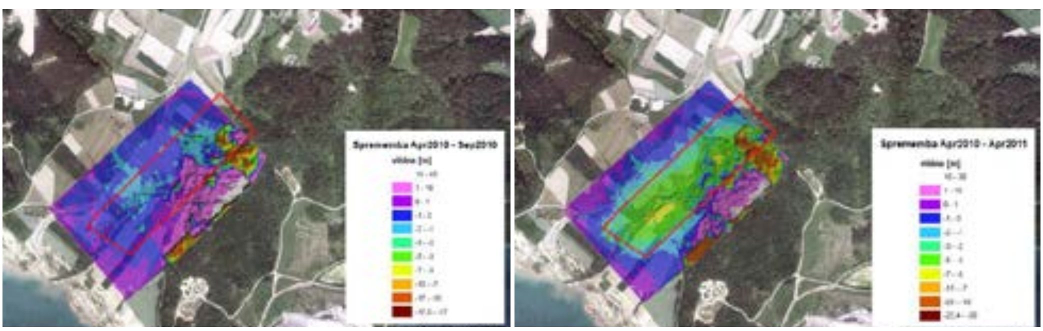

Figure 8: *The results of changes in calculated terrain subsidence on the basis of aerophotogrammetry: April 2010–September 2010 (left) and April 2010–April 2011 (right).*

3.1.3 Bathymetric measurement of lakes

The depth measurement data of the Šalek lakes is essential in monitoring the subsidence area that is filled with water. A comparison of results measurements with previous measurements provides insight into the changes that have occurred within one or more years, [8]. Figure 9 shows a bathymetric map of the Velenje Lake (left) and a 3D model of the lakebed (right). The maximum depth is 63.22 m, the average depth is 23.42 m, the volume is 33,634,785 m³, the surface area is 1,436,183 m² and the altitude is 366.538 m.

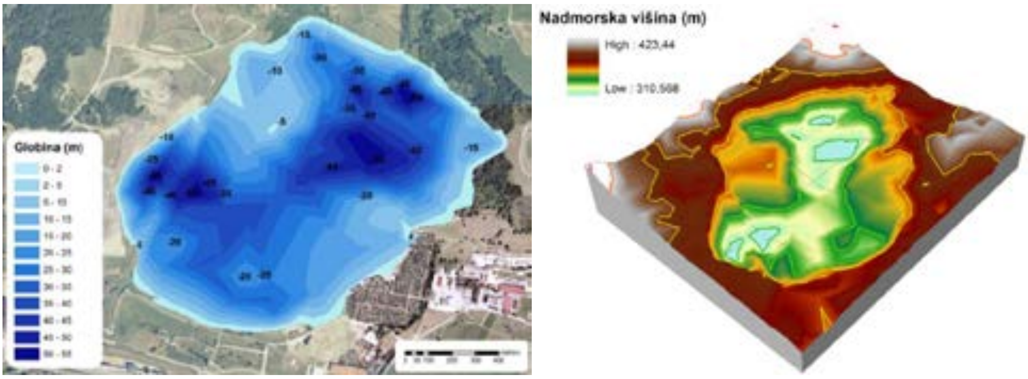

Figure 9: *A bathymetric map (left) and a 3D model of the Velenje Lake lakebed (right).*

3.2 Monitoring building structures

3.2.1 Monitoring building structures with the classic measurement method

The example on Figure 10 shows a facility on which cracks are beginning to appear. In the period from May 2008 onward, the facility has been measured with the height method of geometric levelling through built-in benchmarks. These are included in conducting measurements of the horizontal network by using the method of sets.

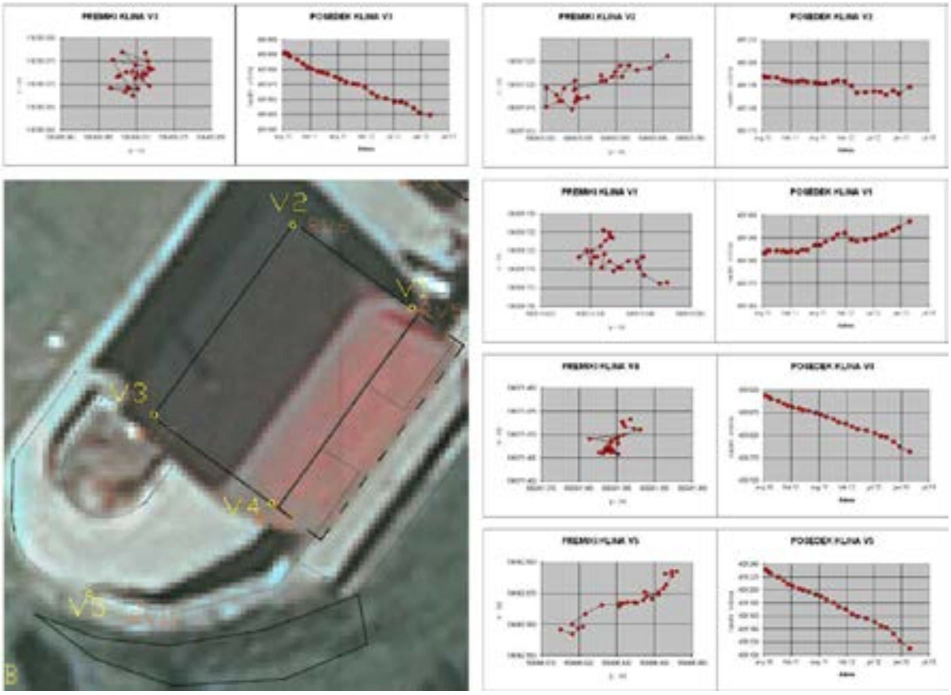

Figure 10: *A graphical display of the results of a monitoring of the movements of the facility over the course of several years.*

The observation network measurements of the NOP II shaft began in December 2012; to date, six measurements have been made using the terrestrial measurement method and the method of geometric levelling, as well as two GNSS period measurements. It is clear from the results of measurements that the movements in the shaft area are minimal (Figure 11), [4].

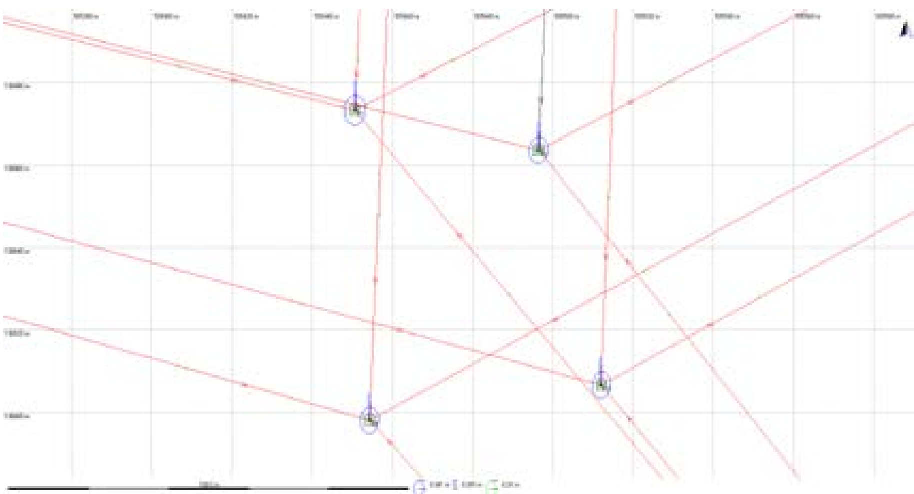

Figure 11: *A graphical result of the GNSS processed points of the base observation network of the NOP II shaft.*

3.2.2 Monitoring the building structures using TLS

Measurements on PV sorting plant building have taken place mostly in order to confirm whether the method is suitable for the observation of such movements. Scannograms of the building in two measurement periods from the processed measurements were obtained, and with the calculation of deviations between pairs of the same points of individual measurements the movements have been calculated (Figure 12). Based on the achieved accuracy of 0.4 mm, which provides detection of movement ≥ 1.3 mm with a 99% probability, it follows that the observed points on the sorting plant building have moved up to 4 cm, [5]. According the results, the necessary procedures for ensuring safety of the building and its reinforcement were predicted. With the process of modelling carried out, the computational processing of data and the results obtained, the 3D terrestrial laser scanning with the scanner proved to be suitable for solving such tasks.

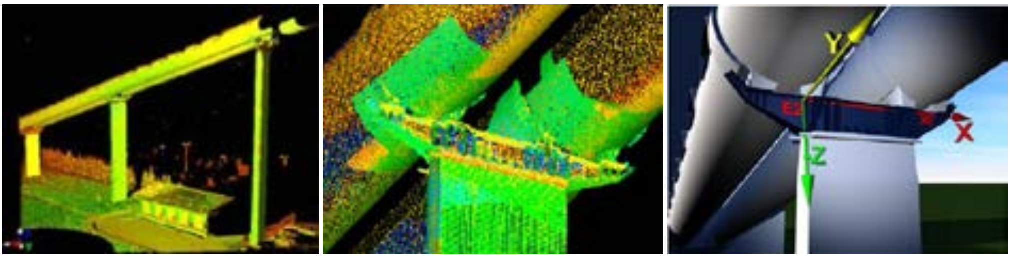

Figure 12: *A scannogram of the observed building (left), a display of a certain detail (middle) and the final model of the building with the coordinate axes shown (right).*

3.2.3 Automatic continuous GNSS system

For the period from 25 September 2010 to 30 April 2013, an analysis was made of the data obtained and the results of observations. Figure 13 (left) shows a coordinate deviation of the observed point GMX E in the direction of axis X (yellow), Y (red) and Z (blue). Of course, on the basis of only a few measurements, conclusions cannot be made on the movement of the observed point, as the accuracy of individual measurements depends on several factors, such as variable meteorological conditions, satellite constellations, mistakes during capturing the data in the 'on the fly' mode. Consequently, the regression functions in real time has also been calculated, which provides a more realistic picture of the change of position of the observed point, and constitutes an effective method for determining whether this is indeed movement or not (Figure 13 right). In this case, the-so called monotonic piecewise cubic interpolation for the regression function was used [9], [10].

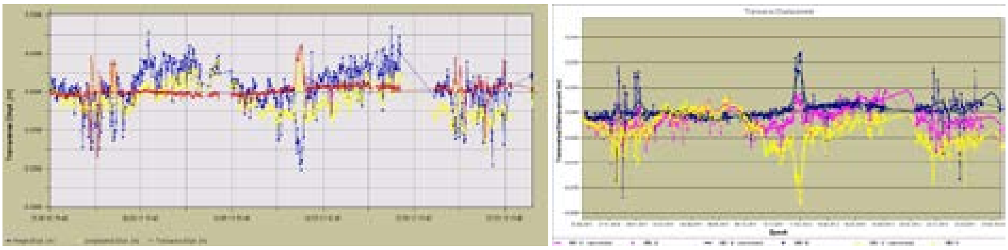

Figure 13: *The coordinate deviation of the point GMX E; X yellow, Y red, Z blue (left), and the coordinate deviation of all three points together with the calculated regression curve; GMX N blue, GMX E pink, GMX S yellow (right).*

The analysis of the accuracy evaluation of the observed points GMX N, GMX E, and GMX S is calculated on the basis of more than 700 twenty-four hour intervals. In case of long-term observations, the accuracy of the measurements within 0.5 mm. Based on that, it can be concluded that the chosen interval of 24 hours is suitable for monitoring a selected building for which no sudden changes are expected, [11].

4 DISCUSSION

The consequences of the mining industry in the Šalek Valley can be seen on the surface as a development of subsidence, which filled with water and led to the formation of three Šalek lakes. With the intent of controlling the events taking place in the extraction area of Velenje Coal Mine, surface movements and vital facilities are monitored consistently. The movement observation system consists of observation networks, which have been used for monitoring over 300 surface points in recent decades. Before 1990, network measurements were conducted only by a combination of triangulation and trilateration for the plane network and a geometric levelling for the height network. However, with the development of satellite technologies and the GNSS system, at the Velenje Coal Mine an observation network on the basis of GNSS measurements was established. Such points represent a much better basis for establishing the coordinates of the mining observation networks' main points, which we then use for measurements of the observation networks. However, surface movements have a negative effect on all neighbouring facilities. By monitoring these movements and the deformation of close industrial and residential facilities, we are able to provide safe working and living conditions. Moreover, we are able to calculate position changes of surface points and facilities in any given time frame using these observations.

As part of monitoring the surface, annual measurements of the Šalek lakes are conducted. These measurements serve the purpose of observing and monitoring the influence of mining on the surface and the reshaping of the terrain. The first measurements of the Velenje lake date back to 1960, but since 1975, regular measurements have been performed on all three lakes.

The extensive geodetic monitoring of the Velenje Coal Mine is constantly being expanded with new measurements and upgraded with the latest equipment. Among the more current techniques, terrestrial laser scanning for the observation of buildings must be mentioned, which was tested by monitoring the movements of the PV sorting plant facility, as well as the automatic GNSS monitoring system, which enables a graphic display of data in real time, which can also be accessed over the internet. Surface monitoring, in contrast, was performed with

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aerophotogrammetry, which proved only partially useful, as forest-covered areas produce inaccurate results. An alternative to this is the LIDAR (Light Detection and Ranging) method, which enables the distinction between the laser beam reflections from actual terrain and those from trees. However, compared to the aforementioned aerophotogrammetry, the price of this method is less favourable.

The main advantages of extended VCM monitoring system, though, are its well-developed methodology, its usage capabilities, the fact that it has been extensively tested, and the manner of assessing the results. The monitoring feature also provides data about the system's accuracy, correct technical procedures, and efficient measures when confronted with known or unknown phenomena.

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