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ORIGINAL RESEARCH ARTICLE

Particularities of deformation processes solution with GIS application for mining landscape reclamation in East Slovakia

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ABSTRACT

The influence of mining activity on the environment on the environment belongs to the most negative industrial influences. Mine subsidence on the surface can be a result of many deep underground mining activities. The present study offers the theory to the specific case of the deformation vectors solution in a case of disruption of the data homogeneity of the geodetic network structure in the monitoring station during periodical measurements in mine subsidence. The theory was developed for the mine subsidence at the abandoned magnesite mine of Košice-Bankov near the city of Košice in East Slovakia. The outputs from the deformation survey were implemented into geographical information system (GIS) applications to a process of gradual reclamation of whole mining landscape in the magnesite mine vicinity. After completion of the mining operations and liquidation of the mine company, it was necessary to determine the exact edges of the mine subsidence of Košice-Bankov with the zones of residual ground motion in order to implement a comprehensive reclamation of the devastated mining landscape. Requirement of knowledge about stability of the former mine subsidence was necessary for starting the reclamation work. Outputs from the present specific solutions of the deformation vectors confirmed the multi-year stability of the mine subsidence in the area of interest. Some numerical and graphical results from the deformation vectors survey in the abandoned magnesite mine of Košice-Bankov are presented. The obtained results were transformed into GIS for the needs of the municipality of Košice City to the implementation of the reclamation activities in the mining territory of Košice-Bankov.

Keywords: Mine Subsidence; Deformation Vector; Geodetic Network; GIS; Reclamation

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1. Introduction

Currently, with the accretive exigencies to protect people's life and property, security has become one of the priority needs and tasks of all countries or their groupings all around the world. In terms of environment protection, since an unspoiled ecosystem is a basic condition for human living, it is necessary to protect people and its property against the negative industrial influences. The influence of mining activity on the environment belongs to the most negative industrial influences. As a result of underground mining of the mineral deposits, there resulted in land subsidence (mine subsidence[1]) in the

[1] Mine subsidence means lateral or vertical ground movement caused by a failure initiated at the mine level, of manmade underground mines, including but not limited to coal mines, clay mines, limestone mines, and fluorspar mines that directly damages residences or commercial buildings. Mine subsidence "does not include lateral or vertical ground movement caused by earthquake, landslide, volcanic eruption, soil conditions, soil erosion, soil freezing and thawing, improperly compacted soil, construction defects, roots of trees and shrubs or collapse of storm and sewer drains and rapid transit tunnels[7].

surface, i.e., caving zone (area), which is dangerous for the movement of people in this zone[1-6]. The underground mining of coal and other minerals creates voids which are subject to collapse. The collapse of these voids may occur at any time ranging from immediate (i.e., while the mineral is being extracted) to 100 or more years after mining. If the collapse causes sinking of the ground surface, the settlement is called mine subsidence[4,6]. Then very great danger and threat to people's lives and their property can be caused by sudden unexpected caving fall of the earth surface over the abandoned mining work[5,8,9].

According to the report of the Illinois Department of Natural Resources[10] and many current theoretical and practical knowledge and scientific studies[4,6,7], it is not possible to precisely predict how long the mine subsidence events will be finished. From the present experience, about 60 to 90 % of the total ground movement occurs within the first few weeks or months of an event. The remaining ground movement continues to develop at a continually decreasing rate and may take 3 to 5 years, or longer.

In order to protect the environment, in particular, the protection of human life and property, it is necessary to examine mine subsidence on the surface[6,11]. The most mine subsidence worldwide with their prediction by means of their modelling are examined through the coal fields[12,13].

Character and size of the subsidence on the surface depends mainly on the geotectonic ratios of rock massif above the mined out area. Knowing the extent of the subsidence trough in mining territories is determining how to prevent the entry of persons into these danger zones. Conditioning factors to establish the extent of the movement of the earth surface above the mined out territory are a geodetic way to survey deformation vectors which can be derived from the processing of measurements at monitoring stations based on these mining tangent territories. 3D (three-dimensional) deformation vectors most adequately characterize movements of ground, buildings and other engineering structures above the mined out territory. Deformation modelling is mostly based on periodic monitoring space changes of various engineering structures, buildings or terrain surfaces by using the surveying classic terrestrial methods, i.e., measuring 3D observation data elements by using classic optic theodolites and leveling instruments in the 40's up-to 80's of the last century or universal electronic measuring instruments — total stations since the 80's of the last century, or by up-to-date progressive surveying satellite navigation technologies and systems, i.e., global positioning system (GPS) and global navigation satellite systems (GNSS) or very seldom and specific surveying technologies such as the surveying technology — interferometric synthetic aperture radar (InSAR) or using other advanced specific terrestrial and aerial and space technologies and techniques[12,14-21]. The deformation vectors are the result of such deformation investigations. The deformation vector with its value gives a global review about the deformation character of the monitored object of interest (earth surface, buildings, engineering structures, etc.) and it also can be used for modelling a future deformation development of such monitored object[4,6,7,15]. Certain specific methods (especially geophysical) for monitoring ground motion must be carried out under controlled large-scale underground work, such as destressing blasting or large-chamber mining in ore and industrial mineral deposits[22,23].

Repeating geodetic measurements in some monitoring stations under deformation investigation of engineering structures, buildings or terrain surfaces can be often complicated in the individual time (periodic) epochs. Monitoring station is presented by a geodetic network with the given structure of the geodetic points on which various geodetic/surveying measurements are realized to determine earth movements or movements of other objects of interest[3]. During the implementation of long-term periodic deformation, measurements can occur in various unpredictable obstacles, for e.g., loss or damage or building-up some established geodetic network points due to construction of new engineering structures and buildings or other construction earth work on the monitoring station zone. It means that the geodetic network with points at a monitoring station has the non-homogenous structure during all periodical geodetic measurements (during deformation survey).

All these or other unpredictable obstacles make it impossible for periodic execution of the original measurement sights realized at the geodetic network of the monitoring station in time of the first (primary or zero) measuring epoch. It means that any periodic measurements cannot be maintained equal conditions for realizing measurement sights. The data homogeneity of whole geodetic network in the monitoring station was disrupted. In these cases, neither a renewal of the destroyed points (reference and object points) at other places and neither substitution of some values in the geodetic network of the monitoring station (which are not measurable in the successive monitoring epochs) by other variables do not make possible to use a standard method in calculation of the deformation vector[4,7,24].

The analysis of time factor of the gradual subsidence development continuing with underground exploitation allows production of more exact model situations in each separate subsidence processes and especially, it provides an upper degree in the prevention of deformations in the surface. Possibility in improving polynomial modelling of the subsidence is conditioned by the knowledge to detect position of so-called "break points", i.e., the points in the surface in which the subsidence border with a zone of breaches and bursts start to develop over the mineral deposit exploitation. It means that the break-points determine a place of the subsidence, where it occurs to the expressive fracture of the continuous surface consistence. 3D deformation vectors locate the places of the break points presenting the subsidence edges[7,11,14,17].

2. Theory to the specific deformation vector solution

The geodetic network structure of a monitoring station can be expressively changed between monitoring epochs (epochs with periodic measurements of the observed geodetic data in the geodetic network) by the above-mentioned changes in an original geodetic network and interference with the geodetic points of such network. The most common and efficient way of geodetic networks processing in geodesy and engineering surveying is the network structures estimate based on Gauss-Markov model. The statistics formulation of Gauss-Markov model is as follows[20,25-28].

$$v = A\left(\hat{C} - C^0\right) - \left(L_{(0)} - L^0\right) = Ad\hat{C} - dL \qquad (1)$$

$$\Sigma_L = \sigma_0^2 Q_L \qquad (2)$$

Where v is the vector of corrections of the measured (observed) values L; A is the configuration (modelling) matrix of the geodetic network or also called Jacobian matrix, i.e., the matrix of partial derivatives of functions $L^0=f(C^0)$ by the vector C^0; $\hat{C}$ is the vector of the aligned 3D coordinate values; C^0 is the vector of the approximate 3D coordinate values; $L_{(0)}$ is the vector of the approximate observation magnitude values of the observed elements in of the first measuring epoch $t_{(0)}$; L^0 is the vector of the approximate observation magnitude values of the observed elements; $d\hat{C}$ is the deformation vector; dL is the vector of the measured values supplements, Σ_L is the covariance matrix of the measured values; σ_0^2 is a priori variance; Q_L is the cofactor matrix of the cofactor matrix of the observations.

It will also be appeared in the changed structures, let us say in a size of the matrixes and vectors A, Q_L, C^0 and L^0. These matrixes and vectors enter into the presupposed model of the net-work adjustment following out from Gauss-Markov model[20,24-26].

2.1 Deformation vector

If between monitoring epochs, there are no changes in the geometrical and observational structure of the geodetic network, then the matrixes and vectors A, Q_L, C^0 and L^0 remain identical for each epoch. Only in such case the deformation vector $d\hat{C}$ can be determined by a conventional procedure according to the following model[6,13]:

In the basic (first) monitoring epoch $t_{(0)}$, we have the vector $\hat{C}_{(0)}$ of the adjusted 3D coordinates of the observed points which are obtained according to Gauss-Markov model:

$$\hat{C}_{(0)} = C^0 + (A^T Q_A^{-1} A)^{-1} A^T Q_L^{-1}\left(L_{(0)} - L^0\right) = C^0 + G\left(L_{(0)} - L^0\right) \qquad (3)$$

In other following epochs $t_{(i)}$, we also obtain the vector $\hat{C}_{(i)}$ of the adjusted 3D coordinates of the observed points according to the equation:

$$\hat{C}_{(i)} = C^0 + (A^T Q_L^{-1} A)^{-1} A^T Q_L^{-1}\left(L_{(i)} - L^0\right) = C^0 + G(L_{(i)} - L^0) \qquad (4)$$

Thus, the deformation vector $d\hat{C}$ will be valid the following equation:

$$d\hat{C} = \hat{C}_{(i)} - \hat{C}_{(0)} = G\left(L_{(i)} - L^0\right) \tag{5}$$

Where L^0 and $L_{(i)}$ are the vectors of the observed magnitude values in the epochs $t_{(0)}$ and $t_{(i)}$.

Now we presuppose a case in which some changes in the established geodetic network structure of the monitoring station are occurred during the monitoring observation epochs, i.e., the geodetic network structure between the basic epoch $t_{(0)}$ and the epoch $t_{(i)}$ are changed. Then the origin matrixes and vectors A, Q_L, C^0 and L^0 will be transformed into the following equations:

$$\bar{A} = A + dA, \quad \bar{Q}_L = Q_L + dQ_L$$
$$\bar{Q}_L = Q_L + dQ_L, \quad L^0 = L^0 + dL \tag{6}$$

According to Equations (6), the vectors $\bar{\hat{C}}_{(0)}$ and $\bar{C}_{(i)}$ of the adjusted 3D coordinates of the observed points in the epochs $t_{(0)}$ and $t_{(i)}$ will be determined:

$$\hat{\bar{C}}_{(0)} = \bar{C}^0 + (\bar{A}^T\bar{Q}_L^{-1}\bar{A})^{-1}\bar{A}^T\bar{Q}_L^{-1}\left(L_{(0)} - \bar{L}^0\right) = \bar{C}^0 + \bar{G}(L_{(0)} - \bar{L}^0) \tag{7}$$

$$\hat{\hat{C}}_{(0)} = \bar{C}^0 + (\bar{A}^T\bar{Q}_L^{-1}\bar{A})^{-1}\bar{A}^T\bar{Q}_L^{-1}\left(L_{(i)} - \bar{L}^0\right) = \bar{C}^0 + \bar{G}\left(L_{(i)} - \bar{L}^0\right) \tag{8}$$

and then the deformation vector $d\hat{C}$ is expressed according to Equation (5) in the form:

$$d\hat{\hat{C}} = \hat{\hat{C}}_{(i)} - \hat{\hat{C}}_{(0)} \tag{9}$$

Which will not express only 3D changes of the geodetic network points between the particular epochs and the deformation vector can be distorted (biased) under the influence of the geodetic network structural changes. Then deformation vector $d\hat{C}$ will not afford the reliable testing information about the concrete deformation consequences.

The presented theory in the cases of some structural changes in the geodetic network can be likely to demonstrate by an analytical way if we compare the deformation vector structures $d\hat{C}$ and $\mathrm{d}\hat{\hat{C}}$ expressed according to Equations (5) and (9). Then the structure of the deformation vector $\mathrm{d}\hat{\hat{C}}$ is expressed according to Equation (9) and the further equation will be valid:

$$d\hat{\hat{C}} = \left[\bar{C}^0 + \bar{G}\left(L_{(i)} - \bar{L}^0\right)\right] - \left[C^0 + G\left(L_{(0)} - L^0\right)\right] = \bar{G}\left(L_{(i)} - \bar{L}^0\right) - G\left(L_{(0)} - \bar{L}^0\right) + \bar{C}^0 - C^0 \tag{10}$$

and on the base of Equations (6) and the linearization of $\bar{G}$ into $\bar{G} = G + dG$, the following derivation will be valid for the deformation vector $d\hat{\hat{C}}$:

$$d\hat{\hat{C}} = (G + dG)\left(L_{(i)} - \bar{L}^0\right) - G\left(L_{(0)} - \bar{L}^0\right) + dC^0 = \bar{G}\left[L_{(i)} - (L^0 + dL^0)\right] + \mathrm{d}G\left(L_{(i)} - \bar{L}^0\right) - G\left(L_{(0)} - L^0\right) + dC^0 = G\left(L_{(i)} - L^0\right) + GdL^0 + dG\left(L_{(i)} - L^0\right) - G\left(L_{(0)} - L^0\right) + dC^0 = G\left(L_{(i)} - L^0\right) + GdL^0 + dG\left(L_{(i)} - \bar{L}^0\right) + dC^0 \tag{11}$$

and finally the deformation vector $d\hat{\hat{C}}$ will be calculated according to the following equation:

$$d\hat{\hat{C}} = \mathrm{d}\hat{C} + \delta\mathrm{d}\hat{C} \tag{12}$$

Equation (12) declares that the deformation vector $d\hat{\hat{C}}$ (calculated with the changed geodetic network structure) is different from its vector of the correct values $d\hat{C}$ only by the term $\delta\mathrm{d}\hat{C}$ (i.e., the correction component of the deformation vector corrections). In this case, the term $\delta\mathrm{d}\hat{C}$ is not generated by spatial movements of the geodetic network points between the individual epochs of measurements, but it is currently generated by changes in the geometric and observational network structure between the particular epochs due to implementation of changes in its point field and also due to changes in measurements in the epochs.

To prevent this problem (so that any depreciation of the deformation vector $d\hat{\hat{C}}$ is not occurred), which is frequently occurred at the deformation investigation, the following procedures are to be used:

The geodetic network must be carefully projected from the point of view of a maximum and permanent providing its reference points and the line sights between the reference and object points during whole monitoring period, especially.

If some reference points were lost or destroyed, new points should be established in enough proximity of these lost or destroyed reference points as possible. Same principle is held for the object points.

If matrixes A and Q_L are expressively changed between the monitoring epochs $t_{(0)}$ and $t_{(i)}$ (for example, in $t_{(0)}$, the geodetic network was measured by a trilateration measurement way, and in $t_{(i)}$ by traverse measurement, and it is necessary to observe more new magnitudes, etc.), then the deformation vector is determined according the following equations:

$$d\hat{C} = C^0 + (A^TQ_L^{-1}A)^{-1}_{(i)}A^T_{(i)}Q^{-1}_{L_{(i)}}\left(L_{(i)} - L^0\right) - [C^0 + (A^TQ_L^{-1}A)^{-1}_{(0)}A^T_{(0)}Q^{-1}_{L_{(0)}}(L_{(0)} - L^0)] \tag{13}$$

And,

$$d\hat{C} = G_{(i)}L_{(i)} - G_{(0)}L_{(0)} - L^0(G_{(i)} - G_{(0)}) \quad (14)$$

Because using the identical C^0 and L^0 is not the problem to adhere in the individual epochs. Or the deformation vector corrections $\delta d\hat{C}$ are calculated according to Equations (7), (8) and (10), so that the deformation vector $d\hat{\hat{C}}$ is then corrected according to the introduced Equation (12).

3. Study case example

3.1 Study territory description

The monitoring deformation station of Košice-Bankov covers a territory around the mine field of the magnesite mine in Košice-Bankov. Košice-Bankov is in the northern part of Košice City, where situated the popular city recreational and tourist center of Košice City. This popular urban recreational zone is located in close proximity to the mine field of the magnesite mine of Košice-Bankov (**Figure 1**).

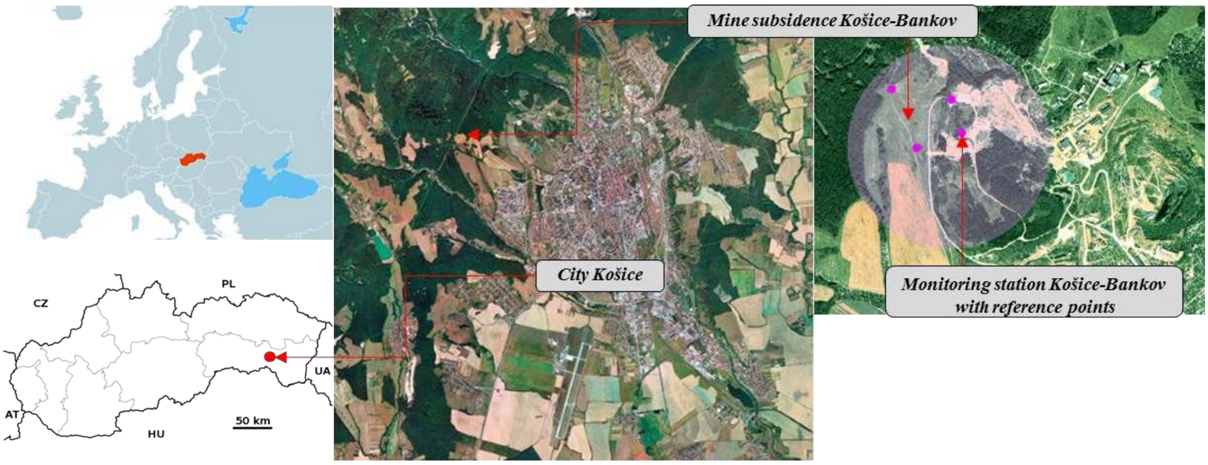

Figure 1. Orthophoto map of Košice City with a detail view of the mine field of Košice- Bankov.

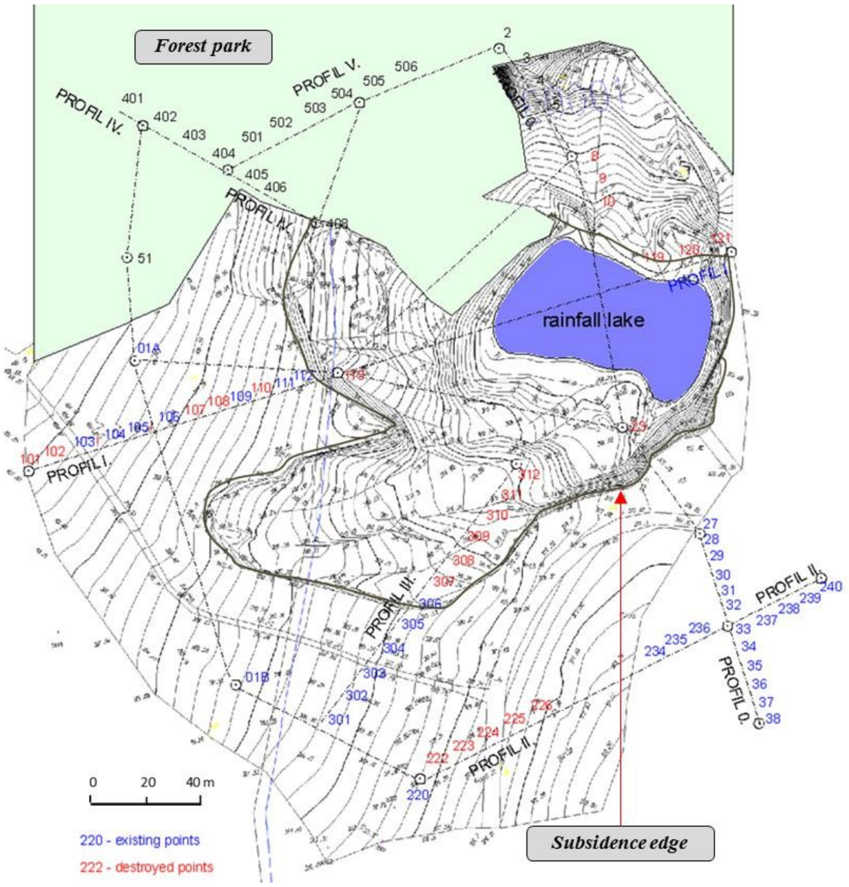

Figure 2. Monitoring station of Košice-Bankov (reference points 01C and 01D – destroyed points).

Problems of mine damages on the surface, dependent on the underground mining at the magnesite deposit, did not receive a systematic research attention in Slovakia till 1976. After that, the requirements for a scientific motivation in the subsidence development following out from rising exploitations and from introducing progressive mine technologies were taken into consideration.

The gradual subsidence development at the Košice-Bankov mine region in the east region of Slovakia is monitored by geodetic way from the beginning (in the end of sixties of the 20th century) of the mine underground activities in the magnesite mineral deposit. The monitoring station project in the Košice-Bankov case was designed and deformation measurements were started in the spring of 1976. The first observed data were taken from this monitoring station in the same year and each year the spring and autumn geodetic terrestrial and GPS measurements were realized. The monitoring station is situated in the earth surface in the Košice-Bankov mine region near by the shaft under the name — West Shaft. The monitoring station is constructed from the geodetic network of the reference points (No.: 01A, 01B, 01C, 01D) and objective points (78 points) situated in geodetic network profiles (**Figure 2**). Some of the reference points were destroyed by the subsidence processes.

Figure 3. Mine subsidence of Košice-Bankov; panoramic view: autumn 2001**.**

Figure 4. Mine subsidence of Košice-Bankov; panoramic view: spring 2002**.**

Figure 3 and **Figure 4** present the panoramic views to the subsidence of Košice-Bankov from the south-west edge of this subsidence in 2001 and 2002 when the magnesite mine was abandoned for two up-to three years.

All surveying profiles of the monitoring station of Košice-Bankov are deployed across and along the expected movements in the subsidence (**Figure 2**). 3D data were firstly observed by 3D (positional and leveling measurements) terrestrial geodetic technology (since 1976) by using classic optical geodetic theodolites and leveling devices for very high precision leveling, later total electronic surveying devices and also devices for GPS/GNSS technology (since 1997), i.e., Trimble 3303DR Total Station, GPS: ProMark2 and GNSS: Leica Viva GS08. Periodic monitoring measurements are performed at the monitoring station of Košice-Bankov twice a year (usually in spring and autumn)[13]. In 1981, some points of this monitoring station were destroyed (defective) and again replaced in same year (points No.: 2, 3, 30, 38, 104, 105 and 227 on the profiles No.: 0, I and II), which was caused by some felling work in close forest crop. The destroyed points were replaced by very precision geodetic way according the origin coordinates.

3.2 Accuracy and quality assessment of the geodetic network

1D, 2D and 3D accuracy of the geodetic network points (the monitoring station of Košice-Bankov) in the East Slovak region was appreciated by the global and the local indices. The global indices were used for the accuracy consideration of whole network, and they were numerically expressed. We used the variance global indices: $tr(\sum_{\hat{C}})$, i.e., a track of the covariance matrix $\sum_{\hat{C}}$ and the volume global indices and $det(\sum_{\hat{C}})$, i.e., a determinant.

The local indices were as a matter of fact the point indices, which characterize a reliability of the network points:

1) mean 3D error:

$\sigma_p = (\sigma^2_{\hat{X}_i} + \sigma^2_{\hat{Y}_i} + \sigma^2_{\hat{Z}_i})^{1/2};$

2) mean coordinate error:

$$\sigma_p = \left[\frac{1}{3}\left(\sigma^2_{\hat{X}_i} + \sigma^2_{\hat{Y}_i} + \sigma^2_{\hat{Z}_i}\right)\right]^{1/2};$$

3) Confidence absolute ellipses or ellipsoids, which were used for a consideration of the real 2D or 3D in the point accuracy. We need to know the ellipsis constructional elements, i.e., semi-major axis a, semi-minor axis b, bearing φ_a of the semi-major axis and ellipsoid flattening f, (f = 1–b/a).

The network quality is mainly characterized by accuracy and reliability. Position accuracy of points can be expressed in addition to numerical and also graphical indicators of the network accuracy, which are the confidence curves and confidence ellipse (confidence ellipsoids in 3D case). Ellipsoids determine a random space, in which the actual location of points will be lie with a probability $1 - a$, where α is the chosen level of significance, according to which the ellipsoids are of different size. In geodetic practice, the standard confidence ellipsoids are used for 3D space. Their design parameters can be derived either from of the cofactor matrix Q_L of the adjusted coordinates, which shall be these design parameters on the main diagonal, or from the coordinate covariance matrix of the coordinate estimations $\sum_{\hat{C}}$ of the determined points, which shall be them on the main diagonal.

All calculated data according to the presented specific theory about the deformation vector estimation in a case of any accepted changes in the geodetic network of the monitoring station are presented in **Tables 1-5**. In general, **Tables 1-5** focused on the accuracy and quality assessment of the geodetic network (**Table 1**: global indices; **Table 2**: mean errors; **Table 3**: absolute confidence ellipse elements; **Table 4**: local indices; **Table 5**: values of deformation vectors[2]).

Table 1. Global indices (spring 1976 / autumn 2014)

Rank	Track	Determinant	Average mean error	Norm
$rk(\sum_{\hat{C}})$ [mm²]	$tr(\sum_{\hat{C}})$ [mm²]	$det(\sum_{\hat{C}})\ 10^{25}$	$\sigma\hat{C}_{pr}$ [mm]	$Nor(d_{\hat{C}})$ [mm]
14/14	7041.901 / 040.879	2.869 / 2.871	22.428 / 23.051	124.218 / 25.043

Table 2. Mean errors (spring 1976/autumn 2014)

Point	m_x [mm]	m_y [mm]	m_z [mm]
2	15.7 / 17.8	32.9 / 44.6	12.5 / 70.9
3	14.8 / 31.2	27.2 / 59.0	30.5 / 69.8
30	21.1 / 27.7	26.5 / 21.9	45.5 / 31.2
38	16.6 / 21.6	16.3 / 10.3	20.1 / 19.1
104	18.2 / 40.4	34.1 / 68.7	55.4 / 79.9
105	28.2 / 34.9	17.1 / 24.2	9.9 / 20.4
227	20.0 / 19.2	8.5 / 8.5	10.9 / 12.5

Table 3. Absolute confidence ellipse elements (spring 1976 / autumn 2014; α = 0.05)

Point	a_i [mm]	b_i [mm]	φ_{a_i} [gon]	f
2	49.9 / 53.5	5.9 / 8.2	172.303 / 172.684	1.8818 / 1.1008
3	40.8 / 30.4	12.3 / 3.5	172.704 / 179.148	0.6985 / 0.8794
30	43.0 / 42.4	18.2 / 20.1	160.340 / 160.054	0.5767 / 0.7821
38	23.5 / 29.8	21.8 / 23.4	40.966 / 41.122	0.0723 / 0.2523
104	47.5 / 79.7	24.0 / 10.1	211.146 / 217.101	0.4947 / 0.8991
105	42.8 / 45.0	15.3 / 19.3	370.337 / 371.011	0.6425 / 0.5851
227	28.8 / 25.4	8.1 / 9.8	19.634 / 12.226	0.7188 / 0.6673

Table 4. Local indices (spring 1976 / autumn 2014)

Point	Mean 3D error σ_p [mm]	Mean coordinate error σ_{xyz} [mm]
2	36.4 / 39.7	25.7 / 19.2
3	30.9 / 28.7	21.8 / 24.7
30	33.9 / 32.4	23.9 / 23.5
38	23.3 / 27.2	16.5 / 12.9
104	38.6 / 17.2	27.3 / 55.4
105	32.9 / 26.2	23.3 / 21.5
227	21.7 / 23.7	15.3 / 19.1

Table 5. Deformation vector values (spring 2007[3] / autumn 2014)

$d\hat{\hat{C}}$ [mm]	Point						
	2	3	30	38	104	105	227
	2.4 / 3.1	-2.9 / -2.8	-8.0 / -9.8	6.7 6.9	-4.0 / -5.7	0.6 / 1.4	9.7 / 10.5

Tables 1-5 comprehend the adjusted mean errors of the individual coordinates, global and local 3D indices and their absolute confidence ellipsoid elements determining 3D accuracy of some chosen replaced points. The numbers in front of the back slash belong to year 1976 when geodetic measurements were started. The numbers after the back slash belong to the autumn of 2014[4] when all geodetic measurements were finished. In 2007, the points No.: 2, 3, 30, 38, 104, 105 and 227

[2] The values of the deformation vectors from the last geodetic measurement (autumn 2014) are compared to the deformation vectors from measurements in 2007 (spring 2017). In 2007, the theory of a specific deformation vector solution presented in the article was verified for the first time in the Košice-Bankov mine subsidence.

[3] 2007 — the year of verification of the theory of the presented specific solution of the deformation vector in the Košice-Bankov mine subsidence.

[4] Deformation survey on the monitoring station of Košice-Bankov without the reclamation work intervention was finished in the autumn of 2014.

were re-stabilized due to small earth construction work needed to the preparation work for a future reclamation of the mining territory of Košice-Bankov. The deformation vector values confirm possibility in the deformation vectors valuation according to the presented theory[20]. However, the deformation vector values need not mean any displacement of the points. Despite the fact that the points of the geodetic network were adjusted in a common way according to the Gauss-Mark model, the deformation vector values can be loaded by accumulating measurement errors. Therefore, for their prominence testing, it is required to carry out testing of the deformation vector by the global and localization test of the congruence (see chapter 3.3). In the last surveying during the autumn of 2014, the deformation vectors on the tested points (No.: 2, 3, 30, 38, 104, 105 and 227) of the monitoring station were ranged from +10.5 mm (point No. 227) to -9.8 mm (point No. 30) (**Table 5** and **Figure 5**).

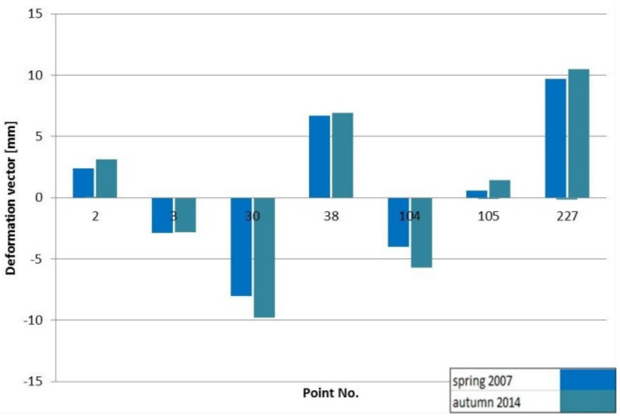

Figure 5. Graphical representation of the deformation vectors on the tested monitoring station points; years: spring 2007 and autumn 2014.

The negative values of the deformation vectors at points No. 3, 30 and 104 represent the opposite trend (direction) of the deformation vector in the space (3D) than at points No. 2, 38, 105 and 227. 3D mean errors (σ_p) were ranged from 17.2 to 39.7 mm (autumn 2014), and the mean coordinate errors (σ_{XYZ}) were from 19.1 to 55.4 mm (autumn 2014) (**Table 4**). After the last geodetic measurement in the autumn of 2014, all points of the monitoring station of Košice-Bankov were destroyed by the reclamation work, i.e., the reference points were removed and the object points were backfilled by the secondary imported soil from various land building and excavation work in and around Košice City.

3.3 Global test of the congruence

Significant stability, respectively instability of the network points is rejected or not rejected by verifying the null-hypothesis H_0 respectively, also other alternative hypothesis[20, 29]

$$H_0 : d\hat{\hat{C}} = 0; \quad H_\alpha : d\hat{\hat{C}} \neq 0 \qquad (15)$$

Where H_0 expresses the insignificance of the coordinate differences between epochs $t_{(0)}$ and $t_{(i)}$. Test statistics T_G can be used for the global test:

$$T_G = \frac{d\hat{C} Q^{-1}_{d\hat{C}} d\hat{C}^T}{k s_0^2} \approx F(f_1, f_2) \qquad (16)$$

Where $Q_{d\hat{C}}$ is the cofactor matrix of the final deformation vector $d\hat{\hat{C}}$; k is the coordinate numbers entering into the network adjustment (k = 3 for 3D coordinates) and s_0^2 is the posteriori variation factor common for both epochs $t_{(0)}$ and $t_{(i)}$.

The critical value T_{KRIT} is searched in the tables of F distribution (Fisher-Snedecor distribution) tables according to the degrees of freedom $f_1 = f_2 = n - k$ or $f_1 = f_2 = n - k + d$, where n is number of the measured values entering into the network adjustment and d is the network defect at the network free adjustment. Through the use of methods, the MINQUE is:

$$s_0^{2t(0)} = s_0^{2t(i)} = \bar{s}_0^2 = 1$$ [20, 29]

The test statistics T should be subjugated to a comparison with the critical test statistics T_{KRIT}. T_{KRIT} is found in the tables of F distribution according the network stages of freedom.

Table 6. Test statistics results of the geodetic network points of the Košice-Bankov monitoring station (autumn 2014)

Point	$T_{G(i)}$	<□≤ >	F	Notice
2	1.883	<	3,724	deformation vectors are not significant
3	3.011	≤		
30	3.720	<		
38	3.721	≤		
104	2.985	<		
105	1.873	<		
227	3.716	<		

Table 6 presents the global testing results of the geodetic network congruence.

Two occurrences can be appeared:

1. $T_G \leq T_{KRIT}$: The null-hypothesis H_0 is accepted. It means that the coordinate values differences (deformation vectors) are not significant.

2. $T_G > T_{KRIT}$: The null-hypothesis H_0 is refused. It means that the coordinate values differences (deformation vectors) are statistically significant. In this case, we can say that the deformation with the confidence level α is occurred.

4. Subsidence in GIS for mining landscape reclamation

GIS of the mining landscape of Košice-Bankov is based on the next decision points[20]: basic and easy observed geo-data presentation, basic database administration and wide information availability. The best viable solution is to execute GIS project as the Free Open Source application available on Internet. The general facility feature is free code and data source viability through the HTTP and FTP protocol located on the project web pages. Inter among others features range simple control, data and information accessibility, centralized system configuration, modular stuff and any OS platform (depends on PHP, MySQL and ArcIMS port)[20,30–32]. Network based application MySQL is in a present time the most preferred database system on Internet and it was applied also on the deformation survey outputs from the monitoring station of Košice-Bankov.

The database part of GIS for the subsidence of Košice-Bankov at any applications is running into MySQL database (**Figure 6**). 3D model of the mine subsidence of Košice-Bankov with GIS multilayers applications were delivered to the reclamation plan of the municipality of Košice City.

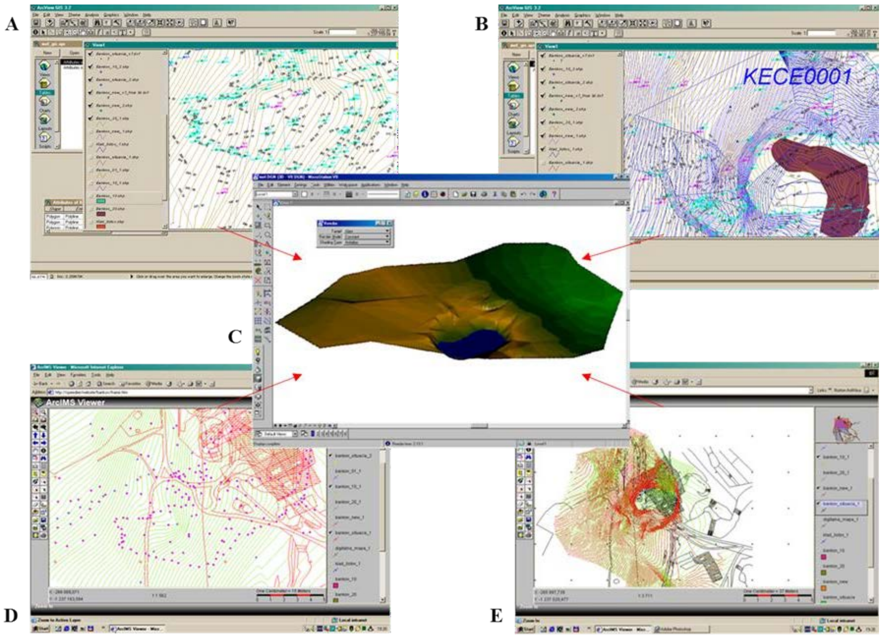

Figure 6. ArcView user interface entity visualization **(A, B)**; MicroStation V8 with Terramodeler MDL application **(C)**; Screenshot of ArcIMS—Application internet interface **(D, E).**

Given the fact that extraction of magnesite has been completed at the mine of Košice-Bankov and these mine workings are abandoned since the end of the 90-years of the last century and whole mining territory of Košice-Bankov with the huge mine subsidence on the conclusions of the deformation investigations are stable, the municipality of Košice City adopted the reclamation plan for that mine landscape. Numerical and graphical presentation of the long-term investigations on the deformation monitoring station of Košice-Bankov with their successive test analyses of the deformation vectors confirmed stability of the mine subsidence and surrounding mining territory. The mine subsidence and by mining activities devastated all surroundings around the mine plant of huge proportions (pit heaps, excavations and other mining earthworks, etc.) began gradually to backfill by a secondary imported soil. The reclamation work on the basis of the investigation geodetic deformation conclusions around the former mining territory of Košice-Bankov began at the beginning of this century. Some final reclamation work was completed in the summer of 2016.

On the territory of the former extensive mine subsidence area, the forest park of Košice-Bankov was built as the environmental green-forest part of the urban recreation zone of Košice City. The mine subsidence began gradually to backfill by imported natural material from many construction and earthworks in Košice City and surroundings of the city. Such sporadic embankment work took too long, i.e., more than years. After completion of the embankment and other earthworks, the forest park of Košice-Bankov was built on the territory of the former mine subsidence (**Figure 7**). It was planted in particular birch trees. These trees are known by their unpretentiousness onto natural base and also by a rapid growth. Currently, birch grove is constituted by five to six year-old healthy tree.

Figure 7. Subsidence and surrounding (Košice-Bankov) after reclamation (2016). Solar collectors in the places of the former waste rock heaps; afforesting (in the background) in the place of the former subsidence**.**

Finalization of the recreation zone of Košice-Bankov was completed in the autumn of 2016. Also, the old tailings piles were reclaimed as well as the devastated surroundings of the former mining plant. On the site of the former waste roc heaps, the solar collectors were built which contribute to renewable energy for Košice City (**Figure 7**).

5. Conclusions

Determination of the deformation vectors as the differences between the adjusted coordinate vectors obtained from two measured monitoring epoch in the geodetic networks is possible if the geometric observation network structure between the individual monitoring epochs is strictly saved. This research article presents the theory and practical outcomes about a possibility of the deformation vector solutions in the geodetic network of the monitoring station in case of violation of the geodetic network structure during the period of monitoring movements of the earth surface. The solved deformation vector affords unreliable image about 3D changes of the geodetic network points in a frame of some specific deformation investigation, e.g., ground movements, mine subsidence, land-slides, dams, engineering constructions, buildings, or other building objects.

The largest differences in all tested elements shown in **Tables 1–5**, especially the largest deformation vectors in **Table 5** and **Figure 5** were occurred on displacement of the point No. 30 and No. 227. Due to the fact that the tested deformation vectors on these points were not significant according to the test statistics, we can declare these points as the static ones. The study case example confirmed availability and applicability of the presented theory on the deformation vector in a special occasion of deformation measurements at mine subsidence, where many violations in the geodetic structure of the monitoring station are occurred. Despite the validity of the verified presented method in solving specific deformation vector in the data, non-homogeneous geodetic network points at the monitoring station may cause a distortion of the deformation effects in the monitoring territory. Therefore, maintaining data-homogeneity of the geodetic network structure should be a priority for whole periodicity of each deformation survey.

The modelling mine subsidence in GIS from the mining territory of Košice-Bankov was delivered to the municipality of Košice city for the solution of the landscape planning to the future environmental rehabilitation of such abandoned old mining region as the magnesite mine of Košice-Bankov. Determination of the deformation vectors of the monitoring station in the undermined landscape of the abandoned magnesite mine of Košice-Bankov was important in delimitation and specification of the edges of the mine subsidence and the edge-punched zones of the subsidence with a lot of cracks and fissures. Very precise identification of the 3D position of such delimitation of the subsidence was a basic document for the plan preparation of the municipality of Košice City for the reclamation of the former mining region of Košice-Bankov as well as and the local ambient by mining activity affected landscape for a comprehensive revitalization and broadening recreational zone in the suburban zone of Košice City. The municipality of Košice City owns 3D model of the mine subsidence of Košice-Bankov in GIS with possibilities of modelling natural and industrial disasters, which largely can be helpful tools for many reclamation work in the landscape ecosystem restoration with the basic elements of safety measures against possible unforeseen and possible consequences of the former mining activities to protect the health and lives of people moving in the forest park located in the former magnesite mine of Košice-Bankov.

Ethics statement

The article was created on the basis of the long-term scientific activities of Prof. V. Sedlák in the field of geodesy and mining surveying, for the purpose of scientific research on deformations of the earth surface due to deep mining. The article presents the specific theory in solution of deformation vectors in mine subsidence. The proposed and applied method of so-called “unconditional” monitoring deformation processes in mine subsidence is verified and confirmed on samples of many geodetic measurements that was made during more than thirty-year research of prof. V. Sedlák in mining sites in Slovakia, especially in the magnesite mine of Košice-Bankov. Some partial data from the last measured geodetic values were processed by Ing. P. Poljakovič, Ph.D. student of prof. V. Sedlák. The results of my long-term research on the proposed specificity of the deformation vector solutions in the Košice-Bankov mining territory have not yet been published in such a complex form as this article presents. Until now, only partial results of the deformation research have been published in the Košice-Bankov mine subsidence.

Conflict of interest

The authors declare that they have no conflict of interest.

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